# Safety Reports Series No. 98

# Design and Conduct of Indoor Radon Surveys

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# DESIGN AND CONDUCT OF INDOOR RADON SURVEYS

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SAFETY REPORTS SERIES No. 98

# DESIGN AND CONDUCT OF INDOOR RADON SURVEYS

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# FOREWORD

For many people, radon in dwellings is the largest contributor to their lifetime exposure to radiation. Requirement 50 of IAEA Safety Standards Series No. GSR Part 3, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, places a responsibility on governments (i.e. national authorities) to "**provide information on levels of radon indoors and the associated health risks and, if appropriate, … establish and implement an action plan for controlling public exposure due to radon indoors.**"

Since the publication of GSR Part 3 in 2014, the IAEA has received many requests from Member States for advice on and assistance in establishing action plans to control exposure due to radon in dwellings. The first step in deciding whether an action plan is needed to control radon exposure of the public is to obtain information on radon concentrations and their distribution in the national housing stock. This is normally achieved by undertaking one or more radon surveys. As a basis for future decision making, it is important that such surveys be designed and conducted in a manner that is representative and free from bias.

The purpose of this Safety Report is to provide States with practical guidance on designing and carrying out representative radon surveys as a basis for decisions regarding action plans to control exposure due to radon in dwellings. Before initiating such surveys, it is good practice to evaluate all available relevant information, as this can help inform decisions on the scope of such surveys and the areas where high radon concentrations are most likely to be found. The results of these surveys can provide a basis for deciding whether a national action plan is needed to control public exposure due to radon indoors.

This Safety Report is jointly sponsored by the World Health Organization. The IAEA expresses its appreciation to C. Fitzpatrick (United States of America) for his work on drafting and reviewing the text. The IAEA officers responsible for this publication were T. Colgan and O. German of the Division of Radiation, Transport and Waste Safety.

## *EDITORIAL NOTE*

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# 1. INTRODUCTION

## 1.1. BACKGROUND

Radon[1] is a radioactive gas that is produced in the ground by the radioactive decay of $^{226}Ra$, which is itself produced by the radioactive decay of $^{238}U$. Both $^{226}Ra$ and $^{238}U$ are present at various concentrations in most rocks and soils. Radon is continuously released into outdoor air, where it is quickly diluted to harmless concentrations. However, when radon enters an enclosed space such as a building, it can accumulate to elevated concentrations and can represent a possible health risk.

For many people, radon represents the major contributor to their lifetime exposure to radiation. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has calculated the global average annual individual dose from exposure to radiation from all sources as 3.0 mSv, of which approximately 80% (2.4 mSv) is due to exposure to radiation from all natural sources. The global average annual dose from exposure due to radon is estimated to be 1.15 mSv, representing just under 50% of the dose from exposure to radiation from all natural sources and just under 40% of the dose from exposure to radiation from all sources [1].

While the average dose from exposure due to radon is 1.15 mSv in a year, situations have been identified in many countries where individuals receive annual doses due to radon that are tens or even hundreds of times higher than this.

Elevated radon concentrations (i.e. radon activity concentrations) indoors are often associated with particular geological formations; however, the only way to accurately determine the concentration of radon in a particular building is to measure it.

Requirement 50 of IAEA Safety Standards Series No. GSR Part 3, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards [2], places a responsibility on governments[2] (i.e. national authorities) to "**provide information on levels of radon indoors and the associated health risks and, if appropriate, … establish and implement an action plan for controlling public exposure due to radon indoors.**"

Since the publication of GSR Part 3 [2] in 2014, the IAEA has received many requests from Member States for advice on and assistance in establishing

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[1] In this Safety Report the term 'radon' refers solely to $^{222}Rn$. In the IAEA Safety Standards Series the term 'radon' refers to any combination of the isotopes $^{220}Rn$ and $^{222}Rn$.

[2] The term 'government' as used in the IAEA safety standards is to be understood in a broad sense, and is accordingly interchangeable with the term 'State'.

action plans to control exposure due to radon in dwellings. The ultimate goal of a national radon action plan is to reduce exposure of the public. This is best achieved by ensuring the use of appropriate building technology by means of building codes: both preventive measures to limit the accumulation of radon in new dwellings and corrective actions to reduce high radon concentrations in existing dwellings need to be developed and applied. For this to be successful, many different parties need to cooperate and a strong communication plan is essential.

Action plans are best developed once there is a good understanding of the extent to which the population is exposed to radiation from radon. This, in turn, means that information needs to be gathered on the magnitude and distribution of radon concentrations in the national housing stock through representative surveys of radon activity concentrations (hereafter called ‘radon surveys’).

## 1.2. OBJECTIVE

This Safety Report discusses the factors that need to be taken into account in designing and carrying out representative indoor radon surveys. It aims to assist national authorities that are considering whether they need to undertake a radon survey and, if so, how to best design and conduct the survey.

## 1.3. SCOPE

This Safety Report addresses the requirement established in para. 5.19(a) of GSR Part 3 [2] to ensure that “Information is gathered on activity concentrations of radon in dwellings … through appropriate means, such as representative radon surveys”. The need for and the purpose of representative indoor radon surveys are discussed, as well as the factors that need to be considered in designing and carrying out such surveys. How the measurement data obtained from radon surveys can be used to develop radon maps is also considered.

This Safety Report draws on the requirements of international standards, the recommendations of international organizations, the scientific literature and direct experience in relation to carrying out indoor radon surveys in a number of States.

While this Safety Report focuses specifically on national and regional surveys to evaluate the distribution of radon in dwellings, many of the same considerations also apply to radon surveys for other types of building.

This Safety Report does not specifically address:

(1) National and regional radon surveys of other buildings with high occupancy factors for members of the public (such as kindergartens, schools and hospitals), or workplaces;
(2) National and regional surveys of thoron in dwellings or other buildings;
(3) Corrective actions to reduce the activity concentrations of radon in buildings;
(4) The design and conduct of a national action plan to reduce public exposure due to radon indoors.

Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

## 1.4. STRUCTURE

As background information, Section 2 briefly summarizes the mechanisms of radon ingress and accumulation in buildings, the associated health effects, and the requirements established and supporting guidance provided in IAEA safety standards.

Section 3 discusses geological information and measurement data that may already be available within a country and that could be used to give a general indication of whether or not to expect high radon concentrations indoors. This information can, in turn, be used to design a pilot survey to better quantify the range of radon concentrations present indoors and to test the logistical aspects of a possible more extensive radon survey.

Section 4 describes possible approaches to the design of representative national and regional indoor radon surveys, including the identification of possible sources of bias. Section 5 discusses challenges in conducting such indoor radon surveys and how these can be minimized.

Appendix I outlines the quality management procedures that are necessary to ensure the accuracy of radon measurements. Appendix II provides an example of a questionnaire that could be used to collect relevant information from participants in indoor radon surveys.

This Safety Report also includes annexes describing the design and conduct of indoor radon surveys in 12 different countries. The countries in which the radon surveys described were conducted — Argentina, Australia, Austria, Bulgaria, Canada, Iceland, Islamic Republic of Iran, Ireland, Italy, Montenegro, the Netherlands and the United States of America — are very different in terms of climate, population and demographics, as well as the extent to which the population is affected by radon. National demographics are often one of the most important factors in designing the survey and in how the results are compiled and presented.

The annex template was designed by the IAEA but it was completed by the individuals or organization responsible for the radon surveys. Each annex summarizes how the results of the radon survey are being, or will be, used to underpin further work. Each annex also discusses lessons to be learned from the conduct of the radon survey, including those aspects of the survey that, with hindsight, might have been managed differently.

# 2. SCIENTIFIC AND REGULATORY BACKGROUND TO INDOOR RADON SURVEYS

## 2.1. SCIENTIFIC BACKGROUND

### 2.1.1. Physical and chemical properties of radon

Radon is a colourless, odourless, tasteless gas originating naturally in rock and soil. It is in the noble gases group of the periodic table of elements and is therefore unreactive and difficult to detect by physical and chemical means. It is, however, radioactive, with a half-life of 3.8 days, decaying primarily via alpha decay. Its decay products are themselves radioactive and have half-lives shorter than that of radon. The decay products of radon are normally referred to as radon progeny and include $^{218}$Po, $^{214}$Pb, $^{214}$Bi and $^{214}$Po. These decay products attach themselves to aerosols.

Because it is a gas, radon is free to move in air and can be inhaled. Radon progeny are also present in air and therefore are also inhaled. Radon gas is quickly exhaled but radon progeny can become deposited in the lungs, where they continue to undergo radioactive decay and give a radiation dose to lung tissue. Thus, most of the radiation dose due to radon is in fact from exposure due to its progeny rather than from exposure due to radon itself.

### 2.1.2. Accumulation of radon in buildings

Radon gas is produced in soil through a series of radioactive decay steps, starting with $^{238}$U. The radon is released into the porous spaces found between rocks and soils; this process is called ‘emanation’. Radon gas travels along a path of least resistance from the ground to the atmosphere, which may involve its seeping into buildings. Radon enters buildings through various routes, such as through cracks in solid floors, construction joints, cracks in walls above and below ground level, gaps in suspended floors, gaps around service pipes and cavities in walls [3].

Radon ingress into buildings can be exacerbated by differences in temperature, and consequently in air pressure, between indoors and the outside, which causes a ‘stack effect’. This occurs when the building’s interior is warmer than the surrounding environment, and the heat inside escapes through the upper floors, drawing in soil air through the ground floor or basement. This effect is greater in the wintertime, when the dwelling is more likely to be heated, more insulated and less ventilated, and when the topsoil around the building may be moisture laden or frozen, leading to relatively greater accumulation of radon beneath the building.

The rate of radon release depends on many factors, including: radium concentration, soil grain size, soil porosity and permeability, soil moisture content, atmospheric pressure and precipitation conditions. Even if these factors are precisely known, it is impossible to determine accurately whether a building will have high activity concentrations of radon without explicit measurement.

Radon can also enter buildings by other means. Building materials containing $^{238}U$ or $^{226}Ra$ may release radon into the indoor environment. Some national legislation places limits on the concentrations of natural sources of radiation that are permitted in building materials (see sections 3.1.6 and 3.1.7 in Ref. [4]). While such legislation is often designed to minimize exposure to gamma radiation, this approach will also limit exposure to radon.

Radon dissolved in the water supply can also contribute to radon concentrations indoors. This can be important in the case of drilled wells used for household water supply, in particular if water bearing layers pass through igneous bedrock such as granite. However, the contribution is not constant as radon is only released when the water is agitated, such as in passing through water taps or shower heads. The same is true for radon in natural gas, but to a much lesser extent; the radon is released from gas cooking tops or gas ovens. Soil is generally the dominant source of radon ingress, especially when radon concentrations in soil are high, but these alternative sources also need to be taken into account as contributing factors.

Apart from the physical factors described above, the lifestyle of inhabitants can also influence the radon concentrations in any given building. For example, dwellings that are closed all day or on weekends are expected to have higher average radon concentrations than if the same dwelling were well ventilated all the time. Whether or not the inhabitants sleep with the windows open or closed (which may also be related to climate) can also be important.

### 2.1.3. Health effects of exposure to radon

The risks to health from inhaling radon and its progeny depend on the mixture of radionuclides present. Radionuclides that emit alpha particles are of particular importance since alpha particles cause more biological damage than beta particles or gamma radiation do inside the body. As mentioned earlier, usually it is radon progeny (rather than radon gas itself) that give rise to most of the risks to health; radon progeny can become trapped in the lungs, whereas most inhaled radon gas is exhaled again.

Alpha particles emitted by trapped radon progeny irradiate sensitive lung cells and can cause damage to deoxyribonucleic acid (DNA). If this damage is not repaired, transformed cells, which pass on damaged DNA as they divide, may become cancerous after years or decades. Effects of this type will not always occur, but their likelihood is proportional to the radon concentration.

The lung cancer associated with exposure to radon is a so-called stochastic effect. A stochastic effect is a radiation induced health effect, the probability of which is greater for a higher radiation dose and the severity of which (if it occurs) is independent of dose. Stochastic effects generally occur without a threshold level of dose below which there are no associated risks of effects.

According to the World Health Organization, "Epidemiological studies confirm that radon in homes increases the risk of lung cancer in the general population" [5]. Chapter 1 of Ref. [5] provides more information on the health effects associated with exposure to radon. Also, the International Agency for Research on Cancer has classified radon as carcinogenic to humans on the basis of a thorough review of epidemiological studies of workers in mines and other workplaces and studies of members of the public exposed to radon in dwellings [6].

An increased risk of lung cancer has been shown for radon concentrations commonly found in dwellings. There is no evidence for a level of radon concentration below which there is no risk [7].

Radon is the second leading cause of lung cancer after tobacco smoking and is one of the main causes of lung cancer among non-smokers. It is well established that for a given radon concentration, lung cancer rates are much higher among smokers than among those who have never smoked [5, 8].

Workers also can be exposed to radon. Workplaces where high radon concentrations are frequently found include water treatment plants, tourist caves and underground workplaces with poor ventilation. There are also workplaces, such as schools, kindergartens and hospitals, where both workers and members of the public may be exposed. Exposure to radon of both workers and the public in such buildings is controlled through the use of regulations and reference levels[3].

In the case of workers occupationally exposed to radon, exposure is controlled through the use of dose limits[4]. Workplaces where recommended activity concentration levels can regularly be exceeded include uranium mines and uranium ore processing facilities and, in some countries, workplaces with activities that involve exposure to other naturally occurring radioactive material.

Lung cancer can take 10–20 years to develop after several years of exposure to radon. This is important to remember when assessing the efficiency of measures for radon reduction, as the actual decrease in the incidence of lung cancer will not be seen in the immediate future, but only after one or two decades.

## 2.2. COMPLIANCE WITH IAEA SAFETY STANDARDS

Requirement 50 of GSR Part 3 [2] states that, in relation to radon exposure in dwellings, "**The government shall provide information on levels of radon indoors and the associated health risks and, if appropriate, shall establish and implement an action plan for controlling public exposure due to radon indoors.**"

In relation to this requirement, IAEA Safety Standards Series No. SSG-32, Protection of the Public against Exposure Indoors due to Radon and Other Natural Sources of Radiation, states in para. 2.4:

> "The national authority should initiate an assessment to determine whether exposure indoors due to natural sources of radiation such as $^{222}$Rn, $^{220}$Rn and gamma rays in dwellings necessitates the development of strategies for radiation protection measures to reduce exposure" [3].

GSR Part 3 [2] further states (para. 5.19(a)) that the government is required to ensure that "information is gathered on activity concentrations of radon in dwellings … through appropriate means, such as representative radon surveys".

Thus an assessment of the activity concentrations of radon in dwellings is required so as to determine possible health risks and the distribution of such

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[3] A reference level is defined as the level of dose, risk or activity concentration above which it is not appropriate to plan to allow exposures to occur and below which optimization of protection and safety would continue to be implemented. The chosen value for a reference level will depend upon the prevailing circumstances for the exposure being considered.

[4] A dose limit is defined as the value of the effective dose or the equivalent dose to individuals in planned exposure situations that is not to be exceeded.

risks within the population. Since the only means of determining concentrations of radon in dwellings is by direct measurement, a programme of radon measurements is necessary. The results of these measurements then provide a basis for deciding on the necessity for producing a national action plan to control public exposure to indoor radon.

### 2.2.1. The role of the national authority

In relation to Requirement 48 of GSR Part 3 [2], SSG-32 [3] (para. 2.3) uses the term 'national authority' "to refer collectively to the regulatory body and all the other authorities and organizations with responsibilities in relation to exposure to radiation from natural sources", noting that "These organizations can include, but are not limited to, organizations involved in radiation protection and public health policy, public and private bodies specializing in radiation measurements, and bodies that set and implement building standards."

Normally, the national organization responsible for radiation protection is the lead organization in a national radon survey. The design and conduct of a representative radon survey, especially if it is national in scope, is likely to involve many of the same authorities and organizations referred to in the preceding paragraph. For this reason, the term 'national authority', as defined above, is used in this Safety Report.

In larger countries where responsibilities may be delegated to regional administrations, it is quite acceptable for the national survey to be carried out through a series of regional surveys. However, the methodology and protocols of the survey ought to be centrally determined so that results from each region are comparable.

It may be more economically viable to contract out aspects of the survey — in particular, recruitment campaigns and radon measurements — to private companies rather than establishing a national infrastructure for this purpose.

Quality control for radon measurements will be a key consideration. This is discussed in more detail in Appendix I.

For the purposes of this Safety Report, the term 'indoor radon survey' is used to denote either national or regional surveys.

# 3. ASSESSMENT OF THE NEED FOR AN INDOOR RADON SURVEY

GSR Part 3 [2] does not specifically require that a national radon survey be performed, but refers rather to ‘representative radon surveys’. Similarly, the general guidance in SSG-32 [3] applies to representative indoor radon surveys, which can be either national or regional.

SSG-32 [3] also discusses, in a general way, the approach to undertaking such surveys and the various factors that need to be taken into account. National experience has shown that many factors have to be considered in deciding on the need for an indoor radon survey, on what the scope of such a survey might be, and on how it can best be designed and conducted. The World Health Organization’s WHO Handbook on Indoor Radon provides information on radon surveys [5].

A decision to initiate an indoor radon survey is not to be taken lightly. Such a survey can be time consuming and can demand considerable human and financial resources. The national authority will need to decide clearly on the purpose and scale of such a survey. In terms of its purpose, a survey may be designed to determine the average radon concentration in the national housing stock, or to identify those areas with the highest radon concentrations indoors, or both.

Once the purpose of the survey has been decided, that influences its scope (i.e. whether it will cover the entire national territory or be confined to certain regions, whether apartments on the upper floors of high rise buildings will be included or excluded, whether both owner occupied and rental properties will be included, and so on).

The national authority will need to convene a working group to assess the need for an indoor radon survey. As existing information may assist in determining the scope of such a survey, the working group may commence by evaluating any such existing information and developing recommendations on the next steps to be taken, if any. Such a working group will normally include scientists and technical experts, such as geologists, radon measurement experts, public health specialists and statisticians.

If analysis of available data indicates that radon is unlikely to pose a health risk, there may be no need to conduct a full national survey. However, this hypothesis would need to be tested with a small scale survey and this would need to be repeated in the future (e.g. every 10 years) to ensure that conditions affecting the ingress and accumulation of radon in buildings remain unchanged.

For example, changes in national policy on energy efficiency could be important, as any reduction in ventilation would be likely to increase radon concentrations indoors. Similarly, climatic processes and geological processes could influence the availability of radon in soil air, while changes in building practices or the use of new types of building materials could result in either an increase or a decrease in radon concentrations indoors.

## 3.1. USE OF EXISTING INFORMATION IN A RADON SURVEY

### 3.1.1. Information on public health

Information on public health at the national level is useful in assessing the need for an indoor radon survey. Any decision to undertake a national indoor radon survey needs to be taken in the context of broader considerations of public health, including the local burden of disease, the average life expectancy and the available budget for health programmes.

Undertaking a radon survey might not be prioritized, for example, in countries with well ventilated housing typical of tropical climates, with a high burden of communicable disease or where the allocation of resources to a radon survey could jeopardize other public health related activities of proven cost effectiveness.

The impact of a radon survey will be greatest in situations in which there is some reason — based on geological data, or national epidemiological data on lung cancer tracked by means of cancer registries or other means — to believe that radon concentrations indoors pose a problem.

Information on tobacco smoking habits and their prevalence and knowledge of policies on passive smoking are also useful.

It is also necessary to ensure, at the outset, that the necessary financial resources and the technical capacity to respond to the findings of the survey will be available.

### 3.1.2. Data on radon measurements

The most relevant information to be evaluated is data from actual measurements of radon in dwellings. Some data may already have been generated through research work undertaken by universities or other organizations. Long term measurements of radon in dwellings over several weeks or months (covering a season or more) will provide the most useful data [5]. Since radon concentrations indoors are influenced by climatic and meteorological factors, short term measurements of a few hours or a few days may not be considered a reliable indicator of long term average values.

In addition to data from radon measurements in dwellings, data may also be available on radon concentrations in other buildings, such as schools and workplaces. In evaluating such data, it is important to bear in mind that, because of differences in construction, ventilation conditions and occupancy, the distributions of radon concentrations in such buildings may be different from those observed in dwellings.

In evaluating data from radon measurements, it is important to note that radon measurements indoors generally follow a log-normal distribution. This means that even if the average radon concentration is relatively low, there will be a small number of measurements that are many times higher. For example, in the United Kingdom the national average radon concentration in dwellings is about 20 Bq/m$^3$ [9], but individual results of over 20 000 Bq/m$^3$ have been reported [10].

To benchmark any existing data, it is helpful to note that the World Health Organization recommends that, to reduce health risks, a reference level be established at or below an average annual radon concentration of 100 Bq/m$^3$. If this level cannot be reached, however, the chosen reference level should not exceed 300 Bq/m$^3$ [5]. This is consistent with GSR Part 3 [2][5], which requires that the reference level not exceed 300 Bq/m$^3$.

Many States that established a reference level set it in the range of 100 to 400 Bq/m$^3$ [11, 12] (see Annexes I to XII). Many States that set reference levels of 400 Bq/m$^3$ on the basis of existing legislation are expected to adjust their reference levels to a maximum of 300 Bq/m$^3$ on the basis of the relevant requirements in GSR Part 3 [2] and in the European Commission Council Directive laying down basic safety standards [13].

The number of measurements and the range of concentrations observed can give some indication of whether or not elevated radon concentrations are likely to be widespread. However, it is important to remember that the results of radon measurements indoors made in one area of a country give no indication of the radon concentrations likely to be encountered in other regions.

Particular attention needs to be paid to the reliability of measurements that may have been made using different methodologies and may not be entirely representative of the national situation.

It can also be helpful to review radon concentrations in dwellings as measured in neighbouring countries, in particular along any land border. National borders often cross geological formations, and practices in housing construction are often similar in neighbouring countries. For this reason, if high radon concentrations indoors are encountered in a neighbouring country, in particular

[5] GSR Part 3 [2] (para. 5.20(a)) requires that the reference level take account of the prevailing social and economic circumstances and states that in general it will not exceed an annual average activity concentration due to $^{222}$Rn of 300 Bq/m$^3$. On the assumption of an equilibrium factor for $^{222}$Rn of 0.4 and an annual occupancy of 7 000 hours, the value for activity concentration due to $^{222}$Rn of 300 Bq/m$^3$ corresponds to an annual effective dose of the order of 10 mSv.

close to the national border, it may indicate that similarly high concentrations will be encountered on the other side of the border.

In the longer term, coordination of policies on radon among neighbouring countries is highly desirable, and the sharing of data from radon measurements can be a useful first step in establishing long term cooperation.

Where no existing data on radon measurements are available, national authorities may be guided by other sources of information, as described in the following subsections.

### *3.1.2.1. Geological data*

Relevant geological data can include information on: radon concentrations in soil gas, near surface $^{238}U$ content, concentrations of uranium series radionuclides in soil and rocks, types of bedrock formations (e.g. granites, phosphatic rocks and shales [14]), topsoil classification and soil permeability, and near surface measurements of gamma dose rates. Such data may be acquired from studies relating to mining exploration, geological surveys, soil surveys, agriculture, environmental monitoring, and so on.

As stated in para. 3.18 of SSG-32 [3], areas where high radon concentrations indoors may be anticipated include:

> "regions where the local geology indicates that there might be elevated concentrations of uranium in the soil and regions of karstic limestone in which underground waters might contain elevated concentrations of radon originating from mineral deposits. In addition, high concentrations of radon indoors might be expected in areas where soil permeability is exceptionally high (such as eskers or ridges composed of permeable gravel), even when the uranium concentration in the soil is not elevated."

However, the absence of such geological regions is not necessarily an indication that radon levels indoors are of no concern; a survey needs to be conducted to test this hypothesis.

### *3.1.2.2. Building materials*

Data on gamma radiation indoors from radionuclides in building materials may indicate elevated radon levels, as the presence of $^{238}U$ or $^{226}Ra$ may increase the concentration of radon indoors. In general, high concentrations of $^{238}U$ or $^{226}Ra$ are more likely to be found in natural building materials; however, the natural components of manufactured building materials can also result in elevated concentrations of radon indoors.

For example, use of building materials made using naturally occurring radioactive material in the form of residues and by-products such as fly ash from the burning of coal can result in high radon concentrations indoors.

The quantity of radon released from building materials into indoor air will depend primarily on the concentrations of $^{238}U$ and $^{226}Ra$ in the building materials, the size of the pores and the surface finish (such as sealed tile as opposed to unsealed concrete). The radon from this source will be additional to any radon present as a result of ingress from the soil immediately below the building, and it is not usually the dominant contribution to radon in the building.

#### *3.1.2.3. Other factors*

Some of the other factors worth considering in an indoor radon survey include the characteristics of the housing stock in the country or region. Where dwellings have been built on stilts or where they have no direct contact with the ground, it is less likely that high radon concentrations will be found indoors. Nevertheless, dwellings built with crawl spaces or basements, though they do not have direct contact with the ground, do often have high radon concentrations indoors.

Dwellings built entirely of wood are less likely to be affected by radon from building materials since wood does not accumulate $^{226}Ra$ or $^{238}U$. Dwellings in the upper floors of apartment buildings are less likely to have high radon levels than ground floor or first floor dwellings. Dwellings that have more ventilation (e.g. those with shutters instead of window glass) are also less likely to have high radon levels [15]. It is important not to omit such dwellings from a radon survey, however. A truly representative radon survey will include all types of dwellings relative to their frequency of occurrence.

### 3.2. UNDERTAKING A PILOT RADON SURVEY

Before commencing an indoor radon survey, especially in the absence of existing information, it is valuable to undertake a pilot survey. While the primary purpose may be to decide whether a full scale radon survey is necessary, as much care and consideration needs to be given to the design of a pilot survey as would be given to a full survey. A pilot survey will normally use the same measurement protocols and have the same quality control requirements as a full scale indoor radon survey.

A pilot survey may be designed for any of a number of reasons, including:

— To provide insight into the range and variability of radon levels observed.
— To gather preliminary data on radon levels in different regions, for different dwelling types, and so on.
— To determine the concentration of radon in soils or outdoor air.
— To test logistical aspects such as:
  - How to recruit participants;
  - What participation rate to expect in the main survey;
  - What types of information to provide participants;
  - What types of information to collect from participants;
  - How to deliver radon detectors to and from dwellings;
  - How to follow up with participants throughout the survey;
  - Which analysis, quality assurance and quality control (QA/QC) to use for radon measurements indoors;
  - How to communicate results effectively to participants.

The number and the spatial distribution of dwellings where radon levels need to be measured will depend on a number of factors, and the pilot survey will need to be designed with input from a statistician. Among the factors that the statistician may need to consider are: the aim of the study and its comparability with any subsequent larger scale study, the spatial variation of relevant factors such as demographics and geology, potential sources of bias, and metrics that may be necessary in the future. In general, the statistician will design the sampling strategy to minimize bias and to provide appropriate weighting for spatially variable parameters.

# 4. DESIGN OF AN INDOOR RADON SURVEY

An indoor radon survey needs to be based on measurements undertaken in individual dwellings rather than in residential institutions, workplaces or schools. An approach that begins with measurements of radon concentrations in public buildings such as schools and day care centres is not desirable because the people in such non-domestic buildings are not representative of the wider population, and the data obtained might not be representative because they are influenced by different factors associated with such buildings. For example, non-domestic buildings have different occupation factors because they are closed on nights and weekends, practices in their design and construction are usually different, and so on.

When designing an indoor radon survey, it is important to develop a database to store and manage the data generated. Developing a database at the outset will help to ensure that the recording and management of data is planned, efficient and secure (see Annex V).

## 4.1. SAMPLING STRATEGY

### 4.1.1. Sampling basis

In designing a survey to assess radon concentrations indoors nationally or regionally, it is important to consider in advance whether the desired output is a spatial distribution of radon levels, a distribution of public health risks, or both. The first is the product of a spatially based or geographically based survey; the second is the product of a population based survey. Paragraph 3.21 of SSG-32 [3] states that with careful consideration, a single survey can be designed to address both geographically based and population density based surveys simultaneously.

The choice of sampling basis gives rise to different issues. For example, where a survey is conducted solely on the basis of population density, only geographical areas covered by large centres of population are likely to be well represented. Regardless of the basis, a spatial sampling unit needs to be defined (e.g. geographical region, geological region, grid square, or a combination). If radon mapping is an intended output, then it is helpful to take this into account at the design stage.

It is desirable, where possible, to align the choice of sampling unit with the sampling unit used for existing spatial data, in particular demographic data and public health data, such as information on tobacco smoking and on the incidence of lung cancer. The alignment of these data sets will enrich the value of the survey findings in terms of the assessment of and communication on population health risks.

Where high rise buildings (apartment buildings) are part of the housing stock, it is important to decide whether to include or to exclude radon measurements on the upper floors. In many cases, upper floors within high rise buildings do not have significant radon concentrations in comparison with ground floors. They may have significant concentrations, however, in cases where the primary source of radon is building materials, or if radon is transported through ventilation shafts or air-conditioning systems from the lower to the upper floors.

Excluding upper floor apartments from the study will provide an overestimate of average radon concentrations in the national housing stock.

However, the study will still be useful in identifying areas with the highest radon concentrations indoors.

### 4.1.2. Sample size

The number of dwellings to be sampled in each spatial sampling unit will depend on a number of factors, including the size of the sampling unit, its representativeness of the total sampling area, the number of dwellings in the sampling unit and the variability expected. The most straightforward approach is to sample a fixed number of dwellings in each sampling unit.

Where the sampling units are not equivalent (with respect to population density, geological characteristics, the administrative units in the country, etc.), a stratified sampling strategy or sample weighting may be necessary.

Experience from different countries, as presented in the annexes to this Safety Report, shows that indoor radon surveys typically cover less than 1% of the total national housing stock, with fewer samples relative to the housing stock being taken in larger countries. In large countries, such a survey can require significant work, and it is up to the national authority to decide what is practicable.

As an alternative approach, certain areas or regions could be prioritized in accordance with the results of a review of existing data or a pilot survey. A phased approach could also be taken, thereby spreading the costs and the conduct of the survey over a number of years. Such considerations need to be accounted for in the statistical design of the survey.

Reference [16] describes a methodology for showing how the number of indoor radon measurements made in an area affects the precision of the data on radon distribution for that area. The study concludes that with only 100 randomly chosen samples, the percentage of dwellings with radon concentrations above the reference level can be determined to an accuracy of within about 25%. For a sample size of 50, this percentage can be determined only to an accuracy of within just over than 30%.

An alternative method is described in Ref. [17]. In this method, a stepwise approach is applied in determining whether radon concentrations in an area are above or below a certain reference value. As a first step, radon concentrations are determined in only a small number of dwellings (typically about five). If the mean value of radon concentration obtained plus one standard deviation is below the reference value, the area is not regarded as a ‘radon priority area’. This approach allows the national authority to balance controlling the cost of making high numbers of radon measurements with achieving an acceptable level of uncertainty in the data collected.

## 4.2. ADDITIONAL OPTIONS IN A RADON SURVEY

As part of any radon survey, it is helpful to collect relevant information from participants through a questionnaire. The survey also provides an opportunity to make other relevant measurements. The design and conduct of a large scale radon survey is resource intensive, so it is prudent to maximize the benefit to be gained. Furthermore, it can be difficult to return to participants at a later date for further information, so it is desirable to gather as much data as possible in a single step.

Questionnaires have been used in many countries to gather useful information on the characteristics of dwellings (e.g. the presence of a basement, whether it is on a ground floor or an upper floor of an apartment building, means of ventilation, the number of occupants, whether it is a permanent dwelling or a seasonal dwelling) that could be of value in directing future surveys and research.

It may be of interest from the perspective of health impacts to ask occupants about their tobacco smoking habits. Since information collected in this way can be helpful in screening out unrepresentative data, it could be useful to obtain the advice of a statistician in developing the questions to be posed.

Furthermore, a methodology has been developed that describes a 'check for representativeness' of radon surveys [18] by comparing the housing characteristics of sample subjects with the housing characteristics described in the national census that was taken most recently before or soonest after the survey. It may be desirable to perform such a check for future radon surveys.

In order to optimize the comparison, it is desirable that the questionnaire in the radon survey contain the same questions, as well as the same preselected options for the answers, as the national census with regard to location, type of housing unit, year of construction and other characteristics as described in the methodology.

The design of such a questionnaire and the selection of questions to be included require careful consideration to ensure that it is not too onerous for the householders who will be completing it. (See Appendix II for a draft questionnaire based on that used in Canada.)

An on-line questionnaire that is linked to the database for the radon survey will be advantageous in reducing requirements for data handling and for administration. However, access to the Internet may not be uniformly distributed across the population, and hence an on-line questionnaire could introduce bias in terms of the financial status of householders, with implications for dwelling type or geographical location.

It may also be of benefit to measure gamma radiation in dwellings where radon is measured (see Annex II). This can be done by issuing a simple thermoluminescent dosimeter or other type of dosimeter together with the radon detector(s). Such dosimeters are cheap and robust, and the measurements made are easy to process and will provide additional information on radiation doses to occupants of dwellings. This may be particularly relevant where it is suspected that building materials might contain elevated concentrations of radionuclides.

## 4.3. RECRUITMENT OF PARTICIPANTS

The means of recruitment of participants for the indoor radon survey is typically by post, telephone or direct contact, or by the use of particular representative citizen groups. For example, in Austria survey participants were recruited from voluntary fire brigades across the country. Local authorities can often be useful, as their offices can be used to advertise the survey and to promote participation.

The choice of approach necessitates careful consideration to reduce the chance of introducing bias into the selection process. For example, random recruitment through landline phone numbers, as used in Canada (see Annex V), may become less representative over time as more households switch to the use of mobile phones.

In areas where, historically, there has been extensive public information about radon, or media coverage of local radon related risks, a cohort of interested householders may be more likely to engage with the survey and therefore may create a bias. Similarly, it may not be appropriate to use historical data on households obtained by commercial radon testing companies, as the data will have arisen largely from tests purchased by interested householders [19].

When radon measurements are to be made in rented properties, a decision needs to be made on whether to approach the occupants of the dwellings or the landlords. On the one hand, there is a potential conflict of interest on the part of the landlord, who may decide not to participate in the survey because if high radon concentrations are identified, it could involve additional expense on his or her part.

However, tenants have a right to know about the radon concentrations in the rented dwelling. Ultimately, national legislation that specifies the relationship between landlords and tenants, and their individual responsibilities, will help in determining the most appropriate means of having radon measurements made in rental properties.

Not all invitees will choose to take part in the survey, and not all of those who take part will complete the process and generate usable data. Experience from Austria, Italy and Montenegro (see Annexes III, IX and X) is that face to face contact with participants improves the participation rate and the completion rate.

When the survey is designed, the anticipated non-completion rate needs to be taken into consideration, and extra invitations need to be issued to compensate for the losses. If a pilot survey has been conducted, it can provide information on the anticipated participation rate and completion rate.

It is useful to ask participants whether they would be willing to be contacted if any follow-up studies are performed. For example, at a future stage, the national authority may wish to estimate the rate of reduction in radon levels; a subset of this cohort of participants would be a useful group to revisit for this purpose. For examples of approaches used to recruit participants, see Annexes I–XII of this Safety Report.

#### 4.3.1. Communication with prospective survey participants

Regardless of the method used to recruit survey participants, consideration needs to be given to communication with prospective survey participants prior to, during and following the radon survey. The purpose of this planned communication is to maximize the participation rate and to facilitate the survey by providing clear instructions and advice to the participants.

Advertising in advance of the study can be valuable in raising public awareness and is likely to increase participation rates. This can be done through print advertising, radio or television commercials, and so on. Locally based radio interviews, public meetings, newspaper articles and the involvement of local politicians can be particularly useful, especially if the survey is regionally based.

It is important that communications convey relevant information on radon gas and its health risks; the importance and benefits of the survey; the authority and competence of the organization carrying out the survey; and the respect that will be shown for the householder in terms of data confidentiality, access to data on their own measurements and advice on any further actions that might need to be considered.

Normally, householders are entitled to obtain the actual results of a radon survey for their dwellings. It is important that householders be assured at the outset that the results will be treated confidentially and that their addresses and the results of measurements will not be disclosed to others. However, it is normal practice in most countries to use survey data for statistical purposes (i.e. the data are published as summary data but data from individual dwellings remain confidential).

It is important to ensure that informed consent is obtained from prospective participants. Consent may be obtained over the telephone as part of the recruitment process or by means of a signed form that is included with the radon detector. It is advisable to obtain legal advice on aspects such as consent and confidentiality before conducting a survey.

Furthermore, as well as obtaining legal advice, it is often instructive to have draft communications and associated documentation reviewed by non-experts, in order to identify missing information or points requiring clarification (see Annex V).

At the commencement of the survey, it is important to give consideration to how participants will be informed of the results of the radon measurements made in their dwellings. This is normally done in writing, and in some countries a phone number is provided for those householders who wish to discuss the results or to obtain additional information.

Householders need to be provided with the actual radon concentrations measured in their dwellings. These measurements need to be put in context with national or international reference levels so that the householder can appreciate the meaning of the results in terms of radon related health risks. It can also be helpful to provide general information on radon and its associated health risks.

Depending on the results, a householder may need to be given information on how radon concentrations can be reduced, including information on where expert advice can be obtained. This aspect is discussed further in Section 5.4 on the reporting of results to participants.

## 4.4. CHOICE OF RADON DETECTOR

There are several methods available for conducting long term radon measurements indoors (with long term generally considered to be a measurement period of two months or longer, though the International Organization for Standardization (ISO) standards for radon in air define it as a measurement period longer than one month [20]). The most widely used method is by means of a type of alpha track detector called a solid state nuclear track detector (SSNTD). These detectors consist of a small plastic substrate enclosed in a diffusion chamber that blocks radon decay products from entering.

The plastic polymers commonly used are polyallyl diglycol carbonate (CR-39), cellulose nitrate (LR-115) or polycarbonate (Makrofol). Exposure to alpha particles alters the surface of the plastic. Following exposure, the plastic is chemically etched in a laboratory to transform the sites of impact to ‘tracks’. These tracks are then counted, usually with an optical microscope, to determine the concentration of alpha particles to which the plastic was exposed. With knowledge of the period of exposure, the average radon concentration can be determined.

SSNTDs are small and cheap, they do not necessitate a background on-site gamma measurement, and they create a permanent high quality record. Once the tracks have been developed in the laboratory, SSNTD elements can be archived and reread several years later if necessary. In addition, modern systems for

SSNTD analysis are automated and can produce a large number of results in a short time, allowing for a high rate of sample processing.

In choosing radon detectors, it is important to take into account that they may produce an overestimation or an underestimation of radon concentrations owing to factors such as sensitivity to thoron [21]. The fading and ageing of CR-39 detectors also needs to be considered and may need to be accounted for, depending on the duration of the measurement [22]. However, accredited laboratories will have considered such issues and will have addressed them in their quality assurance programme.

For more information on detector types, refer to section 2.1 of Ref. [5] and annex 2 of Ref. [3]. For a comparison of detector types in terms of accuracy, see Ref. [23].

## 4.5. DURATION AND LOCATION OF MEASUREMENTS

Radon concentrations indoors typically fluctuate throughout the year, owing to the effects of heating and ventilation (see Section 2.1.2). These effects are less apparent where the climate is more stable throughout the year. Such fluctuations contribute to the variability in radon measurements. For this reason, 12 month measurement periods are generally considered optimal. Three month or six month measurement periods are advocated in some countries.

Radon measurements are often conducted during the ‘heating season’, since radon concentrations indoors tend to be higher during this period, as explained in Section 2.1.2. Thus, a measurement made during the heating season will tend to produce a conservative estimate (i.e. it will overestimate the average) of the radon concentrations indoors.

Undertaking radon measurements during a particular season can pose practical difficulties. In some countries, seasonal correction factors are applied to adjust the measurements to 12 month equivalents. However, the larger the country, the greater the variability in climate, and therefore the less meaningful the use of seasonal correction factors.

Calculating seasonal corrective factors requires a large number of measurements; it is therefore preferable to perform year long measurements instead of correcting for measurements of shorter duration. An approach to the development of seasonal correction factors is described in Ref. [24].

Radon concentrations in a dwelling can be different in each room depending on factors such as radon ingress routes or heating and ventilation levels. Placing multiple detectors in each dwelling is costly. Therefore, as a compromise, two detectors are typically used for one and two storey buildings — one placed in the main living room and the other in an occupied bedroom. This approach ensures that radon concentrations are measured in the two rooms in which occupants spend most of their time.

Using only one detector per dwelling allows for measurements to be made in more dwellings, while using two detectors per dwelling is more accurate. There is thus a balance to be struck between the cost of the project, the number of dwellings to be assessed and the representativeness of measurements. Where measurements are being made in upper floor apartments, and more uniform radon concentrations are therefore to be expected, one radon detector is generally sufficient.

Guidance on measuring radon concentrations in dwellings [25–27] has been published in several countries, and is also provided in section 2.2.1 of Ref. [5]. These guidance publications advise avoiding the placement of detectors in locations that may affect the representativeness of the radon measurements. Examples of such locations are near windows where air flow may affect the measurements, and near heat sources which may affect the performance of detectors.

## 4.6. QUALITY ASSURANCE AND QUALITY CONTROL FOR RADON MEASUREMENTS

QA/QC is an important part of ensuring that measurements are made as accurately as possible and that biases are reduced. Generally, a large part of QA/QC for radon surveys is performed in the analytical laboratory (further details on elements of a laboratory QA/QC programme are outlined in Appendix I), but some additional steps can be taken to ensure the accuracy of results in the measurement stage of a survey.

These additional steps include precautionary steps such as minimizing storage times of radon detectors before and after exposure, sealing detectors to ensure that there is no exposure due to radon during shipping, and providing advice on proper placement of detectors within the dwelling.

It is essential that the quality considerations be extended to include these steps. Some compromise on quality may be inevitable, but it is important to make every effort to quantify any associated errors or biases.

## 4.7. SOURCES OF BIAS

In any indoor radon survey there is potential for biases (meaning anything that could cause the survey not to be accurately representative) at nearly every stage in the process. Some aspects of bias have been discussed in previous sections, such as biases relating to interested householders, tampering with detectors, seasonal measurements, placement of detectors, and so on.

The annexes include various examples of when and how to account for biases encountered in typical national and regional indoor radon surveys. Possible biases need to be identified but they cannot be entirely avoided. It is more important to understand what the likely biases are and to account for them to the extent possible.

# 5. CONDUCT OF AN INDOOR RADON SURVEY

## 5.1. DISTRIBUTION AND COLLECTION OF DETECTORS

Secure and consistent distribution, placement and delivery of radon detectors to the measurement laboratory are critical to the success of the radon survey. In many countries this is done entirely using the postal service.

Where this is not possible, direct placement and collection by officials or volunteers may be required, but this will be more time consuming (see Annex VII). The deployment can also be done by people hired and trained for this purpose by the organization responsible for the survey.

The following list sets out some useful considerations if the postal service is used:

- Package the SSNTDs in sealed radon proof bags or containers, with a clear explanation that the bag or container has to remain sealed until the detector is ready for use.
- Include clear instructions (consider adding sample photographs or Internet web site links to an on-line instructional video) for deploying the detector(s) in a suitable location (best place is in the middle of the room, hanging from the ceiling).
- Include a pre-addressed return envelope or package with clear instructions on how and when to return the detector(s); depending on the detector type, this return package may need to include a sealable bag or container.
- Label detectors to stress the importance of accurately recording the start date of the test, the end date of the test and the location of the detector(s). This is important because the duration of the measurement is required to accurately calculate the average radon concentration.
- Include a questionnaire to capture ancillary information or a link to an on-line portal where such information can be submitted.

— Provide a checklist to remind the participant to return all elements of the package and to be sure to submit the start date and end date of the test.
— Include pictures of the detector and explain that the detector should not be opened or altered, to avoid damaging it.
— Some radon detectors on the market operate with an on/off switch. When delivered to the home, the detector is off, and the switch must be turned to the on position to initiate the measurement. At the end of the measurement period and before being returned for analysis, the detector is turned off. Normally, radon-proof bags are not required when such detectors are distributed and collected through the postal service. However, very clear instructions are required, to ensure that the survey participants are aware of how to initiate and terminate the radon measurement.

It is helpful to provide contact telephone numbers, email addresses and web site addresses so that participants' questions can be answered during the testing period. Experience from the study in the Islamic Republic of Iran (Annex VII) shows that it is helpful to follow up with participants during the measurement period to maintain their awareness of the various considerations and to address any concerns.

When using the postal service to collect detectors, it is effective to send a message to participants by means of a telephone call, email or text message when the test period has elapsed, to remind them to return the detectors.

## 5.2. VALIDATION AND ANALYSIS OF DATA

Before inclusion in the final analysis, each measurement result needs to be validated (i.e. authenticated on the basis of available information) to confirm that the measurement was taken in line with the agreed protocol and that the location of the dwelling and other required information is available. For example, if an essential piece of information is missing, such as the start date or the end date of the measurement, then that measurement will not be validated.

It has been shown that the distribution of radon concentrations in dwellings approximates a log-normal distribution [28] and that this model fits the distributions of radon concentrations well for concentrations up to about 200 Bq/m$^3$ [29]. Data need to be tested for log-normality (methods for testing for log-normality are described in Ref. [28]) and any outliers need to be reviewed.

Data from the questionnaire will be of assistance here, especially in checking for representativeness as discussed in Section 4.2. As is discussed in Appendix I, it is important to correct measurement data to account for background radon levels.

The data can be summarized for the survey as a whole to generate an overall average radon concentration indoors for the area covered by the survey. The average radon concentration can be calculated based on the arithmetic mean, the geometric mean, or both.

Calculating the arithmetic mean puts greater weight on higher radon concentrations, while calculating the geometric mean, which represents the central tendency or ‘typical value’ of the data, tends to dampen the effect of very low or very high values. Advice on statistics will be useful in making a decision on how best to present the results in a way that is meaningful.

The average value can be calculated for individual sampling units (e.g. grid squares or administrative zones) provided that adequate numbers of samples are available for each unit. The data derived can be screened to identify the number of dwellings with radon levels in excess of a reference level. The locations of these dwellings may be of interest in relation to geological data or other data.

These derived data can be combined with data from the questionnaire in order to identify the number of persons exposed at these levels and possibly also the type of dwelling that typically yields high radon levels. More detailed examples of this and further descriptions of past data analyses can be found in Annexes I–XII.

Radon related risks for each sampling unit can be calculated with regard to a reference level. Areas where the average radon concentration exceeds the national average concentration are often called ‘radon prone areas’. These areas are often also referred to as ‘radon risk areas’, ‘high radon areas’, ‘radon priority areas’, ‘radon affected areas’, and so on, with the definition varying by country.

International Commission on Radiological Protection (ICRP) Publication 103 refers to an area in which the concentration of radon in buildings is likely to be higher than the national average [30]. ICRP Publication 115 and ICRP Publication 126 discuss a geographic area or an administrative region, defined on the basis of surveys, indicating a significantly higher level of radon concentrations than in other parts of the country [31, 32].

The European basic safety standards oblige European Union Member States to “identify areas where the radon concentration (as an annual average) in a significant number of buildings is expected to exceed the relevant national reference level” [13]. For example, Ireland defines a radon risk area as an area where 10% or more of dwellings are predicted to have radon concentrations above the national reference level for radon of 200 Bq/m$^3$ (see Annex VIII). In the United Kingdom, radon affected areas are defined as areas in which 1% or more of dwellings are likely to exceed the national action level of 200 Bq/m$^3$ [10].

## 5.3. MANAGEMENT AND MAPPING OF DATA

The results from an indoor radon survey will represent a large data set consisting of radon measurements and associated data. These will be a valuable resource for informing policy and research on radon, for prioritization of resources for corrective actions[6], and for underpinning the development of any future radon action plan.

As already discussed, it is desirable to design a database that can store the data and support its management and analysis. Because the spatial nature of the data lends itself to a data management approach based on a geographic information system, development of a radon map is common.

With the results of a representative geographically based radon survey, maps can be created identifying high radon areas. A radon map can serve two purposes: communicating radon distributions to decision makers and the public, and assisting experts in developing a graded approach to reducing exposure due to radon and associated risks. It is important to distinguish between these two roles, as the first requires consideration of the principles of communication of risks and the interpretation of map related information by non-specialists.

Applying a graded approach means that dwellings and areas with higher radon concentrations are given a high priority when actions are under consideration following the measurements. A graded approach can be adopted for preventive measures in new buildings, based on radon maps or the identification of radon risk areas (see Ref. [33]). In the radon survey conducted in Ireland, the benefit of a graded approach was discussed:

> "To date radon measurements have been made in approximately 20,000 houses which represents only 1.5% of the national housing stock in 2000 (GeoDirectory). Of the estimated 91,000 high radon houses, approximately 2,300 (2.5%) have been identified. By targeting future surveys in the High Radon Areas, and carrying out measurements in approximately 300,000 houses, approximately 60,000 high radon houses could be identified — this represents a detection rate of 1 in 5 houses measured. In contrast, to identify the 31,683 high radon houses located outside these High Radon Areas measurements would have to be carried in over 1,020,000 houses — a detection rate of 1 in 30. It is obvious that surveys targeted at the High Radon Areas will provide a higher rate of detection and a better return of resources invested" [34].

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[6] The IAEA safety standards use the term 'corrective actions' when referring to work undertaken to reduce radon concentrations indoors. Many national programmes use the term 'remediation' or 'mitigation', with a similar meaning intended.

It is important to keep in mind that radon maps are only a probabilistic tool for policy decisions such as prioritization; they cannot be used to derive radon concentrations for an individual dwelling. Equally, the boundaries of the sampling units inaccurately create an impression of a hard spatial boundary to radon related risks.

Owing to the log-normality of the distribution of measurement data on radon indoors, a sampling unit with a low average radon concentration can contain extreme values. For this reason, further testing for high radon levels is always warranted and, as more measurement data become available, the categorization of individual sampling units may change.

The potential for non-experts to misinterpret map based data on radon levels is not to be underestimated. If it occurs, it can be time consuming to correct. This is the case in particular where maps are wrongly interpreted in material that is widely distributed to and read by the public.

One possible option for publishing risk maps for radon is to include a disclaimer and a reference to where the correct interpretation of the map can be found. Another is to limit the distribution of such maps to policy makers and experts only. However, neither of these options is ideal; disclaimers are rarely fully read and understood, and maps are important communication tools that help to raise awareness of radon related risks among the general public.

As discussed in Section 4 on design of an indoor radon survey, ideally the units of the radon map would align with existing national geographical or administrative units or with other national spatial data. The alignment of radon related data with other data allows for the comparison of values for radon levels with other data such as data on geological factors, population health, population density, and so on. Examples of how data on radon levels have been compared with other data sets are presented in Annexes III and V.

Data on radon levels indoors can be displayed in different ways on a map: by using the measurement values directly or as summary data. The results can be described in a unit (geological, administrative or grid cell unit) with descriptive statistics (e.g. arithmetic mean or median (see Annex III)); as a predicted percentage of dwellings above a reference level (see Annex VIII); or as a risk index (multivariate classification, as in for example, the United States of America and Czech Republic).

The radon map can show classifications in multiple levels of radon related risks. Different approaches are taken in different countries; for example, three risk categories (high, medium and low) are used by the United States Environmental Protection Agency [35], whereas in Ireland, five classes are presented (see Annex VIII).

## 5.4. REPORTING OF RESULTS TO PARTICIPANTS

Once results have been obtained and verified, a report can be issued to each participant. The report will generally state the radon concentrations measured and the average concentration measured by all detectors placed in each dwelling, with supporting information on what the results mean.

It can be helpful to include general information on radon and tailored information if the radon levels are high. This tailored information may include information to allay unwarranted concerns, to support the householder in progressing to corrective actions and to direct the householder to further informational resources, telephone hotlines and so on. The language used to convey this information needs to be as clear, concise and easy to understand as possible.

If a national reference level with which to compare the results has not yet been set, information may be given in comparison to the maximum reference level of 300 Bq/m$^3$ set in GSR Part 3 [2]. As a first step, information on basic measures for radon reduction can be given to the householder. Some such measures are described in Refs [25, 36, 37].

Given that a radon survey was undertaken, the regulatory body will already be aware that elevated concentrations of radon are likely to be found in at least some dwellings. It is sensible to prepare for this outcome well in advance by establishing connections with civil engineers and other building professionals. Such professionals can assist in preparing a set of frequently asked questions and answers concerning corrective actions to reduce high concentrations of radon in dwellings.

Further information can be obtained from the IAEA radon flow chart [38], which summarizes the relationship between the various components of a national radon action plan.

# Appendix I

# QUALITY MANAGEMENT FOR RADON MEASUREMENT LABORATORIES

## I.1. QUALITY ASSURANCE AND QUALITY CONTROL

All laboratories providing radon measurement services need to establish and maintain a QA/QC programme [39]. A QA/QC programme contributes to greater transparency, consistency, comparability and confidence in the results of radon measurements.

Very often, the radon measurement laboratory will purchase radon detectors commercially from an external supplier. An important aspect of the QA/QC programme is therefore to ensure the ongoing quality of the detectors and their compliance with criteria established in the purchase agreement.

QA activities include a planned system of reviews conducted by personnel not directly involved in the development of radon measurement services. Reviews, preferably by independent third parties, are performed following the application of quality control procedures. Quality control activities include general methods such as accuracy checks on data acquisition and calculations, and the use of approved standardized procedures for calculations, measurements, estimating uncertainties, archiving information and reporting.

Passive radon detectors (SSNTDs) issued by professional laboratory services can be used to make integrated radon measurements that are accurate to within 10% for radon concentrations within the range of reference levels adopted in many countries. As concentrations of radon and durations of measurement decrease, the inherent uncertainty in the results of the analysis will increase. This is mainly because uncertainties in radioactivity measurements follow a Poisson distribution for uncertainty [40].

In order to conduct a robust indoor radon survey, it is important that the analytical service laboratory (or national radon laboratory) providing radon measurement services have a QA system in place. The QA system is necessary to demonstrate that the analytical laboratory is capable of producing accurate results from long term measurements on radon indoors.

Some States require accreditation of analytical laboratories per Ref. [41], while others have developed their own certification systems (see Annexes V and VIII).

Other States may require that a QA system be in place for the provision of radon measurement services. It is important that the national authority seek out radon measurement laboratories that use formal QA systems.

It is also important that the QC system of the analytical laboratory providing radon measurement services take account of ‘end to end’ sources of variation in the entire measurement process and ensure the following, as appropriate [26]:

- Reference samples or known exposure measurements consisting of detectors that have been exposed to known radon concentrations in a radon calibration chamber are used to monitor the accuracy of the entire measurement system. Reference samples make it possible to keep track of the performance of the detectors used and the overall analytical scheme. Reference or QC measurements could be conducted at a rate of approximately 3% of all measurements.
- Check standards. Detectors exposed in a national reference chamber and run through the entire analytical scheme are used to monitor the performance of the counting system itself.
- Passive detectors utilized for national radon surveys are tested for their sensitivity to thoron. The isotope $^{220}Rn$ has a short half-life of 56 seconds and hence the interference that $^{220}Rn$ presents to analysis for radon is a function of the diffusion path length. Normally the interference that thoron gas presents to radon measurements is low. This can be tested by exposing the radon detectors to known concentrations of $^{220}Rn$ under controlled conditions, and then calculating the apparent results for radon concentrations that these $^{220}Rn$ concentrations yield.
- A subset of radon detectors are used to check and monitor background radon levels. These background levels can derive from the manufacturing process or can accumulate during transport if the detectors are not appropriately packaged. Such radon detectors are sometimes referred to as ‘blank detectors’ and typically consist of 3% to 5% of the total number of radon detectors in any shipment.
- These blank detectors are set aside from each detector shipment, are kept sealed and in a low radon environment, are labelled in the same manner as the field detectors to preclude special processing, and are analysed in the same way as all other radon detectors. The results are used for two purposes: to modify individual measurements by subtracting the average radon concentration and to continuously monitor the quality of the radon detectors purchased from the supplier(s).
- Laboratory intercomparisons are arranged with other national or international laboratories. Such intercomparisons are often required as part of ISO accreditation. Participation in such exercises is a powerful tool for controlling the quality of the measurement results.

— Duplicate detectors are used to check the quality of the measurement results. They allow an estimate to be made of the relative precision. A duplicate detector is a detector that is collocated with another detector and is deployed for the same measurement period. The precision of duplicate measurements needs to be monitored and recorded in the QA records. The statistical relative percentage difference (RPD) can be calculated from duplicate measurements [26]:

$$\text{RPD} = \frac{\text{Test 1} - \text{Test 2}}{\overline{\text{Test 1} + \text{Test 2}}} \times 100 \tag{1}$$

where

| | |
|---|---|
| RPD | is the relative percentage difference; |
| Test 1 – Test 2 | is the absolute value of the difference between the two duplicate test results; |
| $\overline{\text{Test 1} + \text{Test 2}}$ | is the mean of the two duplicate test results. |

Ranges of acceptability for RPD and instructions on what to do in the case of a failure of QA/QC (e.g. undertake an investigation or conduct a retest) need to be indicated in the QA scheme.

## I.2. CALIBRATION OF DEVICES

Measurement systems need to be calibrated by means of comparison with exposures due to radon that are conducted by a national reference laboratory or other reference laboratory. Each batch of detectors needs to be calibrated to ensure consistent standards of operation.

Calibration measurements need to be conducted to determine and to verify the conversion factors used to derive the results of concentration measurements. These factors are generally determined for a range of concentrations and exposure times, and for a range of other exposure conditions and analytical conditions pertinent to the particular device and the expected radon concentrations.

Typical exposure levels used to calibrate devices that measure radon concentrations in dwellings range from a few hundred kBq/m$^3$ × h (e.g. 220 kBq/m$^3$ × h, corresponding to about 100, 50 and 25 Bq/m$^3$ for exposure periods of 3, 6 and 12 months, respectively) to several thousand kBq/m$^3$ × h (e.g. 6000 kBq/m$^3$ × h, corresponding to about 3000, 1500 and 750 Bq/m$^3$ for exposure periods of 3, 6 and 12 months, respectively) [42].

Determination of these calibration factors is a necessary part of the laboratory analysis. These procedures for calibration measurements, including the frequency of tests and the number of devices to be tested, are normally specified in the QA programme.

## Appendix II

## EXAMPLE OF A QUESTIONNAIRE FOR PARTICIPANTS IN AN INDOOR RADON SURVEY[7]

### CONTACT DETAILS

Name:

Address:

Telephone number:

Email address:

### WHERE DID YOU PLACE YOUR DETECTOR?

*On what floor did you place your radon detector?*

- □ Basement (underground)
- □ First floor (at ground level)
- □ Second floor (level above ground level)
- □ Higher floor (SPECIFY)

*In which room in your home was the detector placed?*

- □ Living room
- □ Bedroom
- □ Other (SPECIFY)

### DETAILS ABOUT YOUR HOME

*What type of home do you live in?* (CHECK ONE)

Single detached home, that is, a single house on its own property:

- □ Bungalow
- □ Two storey

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[7] This sample questionnaire is based on a questionnaire used in Canada [43].

- ☐ Three storey
- ☐ Split level

A semi-detached home, that is, a home that shares a common wall with another home:

- ☐ Side by side
- ☐ Row house

Other

- ☐ Trailer/mobile home
- ☐ Prefabricated home
- ☐ Apartment
- ☐ Other (SPECIFY)

*Approximately when was your home originally built?* (CHECK ONE)

- ☐ 1920 or before
- ☐ 1921–1945
- ☐ 1946–1960
- ☐ 1961–1970
- ☐ 1971–1980
- ☐ 1981–1990
- ☐ 1991–2000
- ☐ 2001–2009
- ☐ 2010–
- ☐ Not sure

*Does your home have a basement?*

- ☐ Yes, a full basement (that is, underneath the entire building)
- ☐ Yes, a partial basement (that is, underneath part of the building)
- ☐ The house sits directly on the ground with no basement

*Does anyone in your home regularly use/sleep in the basement?*

- ☐ Yes
- ☐ No

*What type of foundation does your home have?* (CHECK ALL THAT APPLY)

- □ Poured concrete
- □ Brick
- □ Stone
- □ Wood
- □ Other (SPECIFY)

*What type of heating fuel or energy do you use in your home?* (CHECK ALL THAT APPLY)

- □ Natural gas
- □ Electric
- □ Oil
- □ Geothermal
- □ Wood
- □ Solar
- □ Other (SPECIFY)

*What type of heating system is it?* (CHECK ALL THAT APPLY)

- □ Forced air
- □ Radiant (water)
- □ Baseboard
- □ Other (SPECIFY)

*Does your home have air-conditioning?*

- □ Yes
- □ No

*How is water supplied to your home?*

- □ Municipal distribution system (piped/trucked in)
- □ Private well water
- □ Other (SPECIFY)

*Does anyone in your household smoke?*

- □ Yes
- □ No

*In the past year, have you had any of the following renovations done in your home?* (CHECK ALL THAT APPLY)

- □ Renovated or upgraded the ventilation system (excluding kitchen fans or bathroom fans)
- □ Made changes to or upgraded the main heating system
- □ Made an addition
- □ Finished or converted the basement
- □ None of these renovations were done in the past year

**PREVIOUS RADON MEASUREMENTS**

*Have you tested your home for radon in the past?*

- □ Yes
- □ No

*What type of test was performed?*

- □ Short term (7 days or less)
- □ Long term (over 30 days)
- □ Other (SPECIFY)
- □ Don't know

*What measurement of the radon level was provided with the test results?* (RECORD THE NUMBER AND, IF YOU KNOW, THE MEASUREMENT UNIT)

NUMBER:

- □ pCi/L — picocuries per litre
- □ $Bq/m^3$ — becquerels per cubic metre
- □ Don't know

I understand that the information provided in this survey and the results of the radon measurements carried out in my home may be used for statistical purposes but will not otherwise be communicated to others.

Signed:

Date:

# REFERENCES

[1] UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION, Effects of Ionizing Radiation, Annex E: Sources-to-Effects Assessment for Radon in Homes and Workplaces, United Nations, New York (2009).

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

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, WORLD HEALTH ORGANIZATION, Protection of the Public against Exposure Indoors due to Radon and Other Natural Sources of Radiation, IAEA Safety Standards Series No. SSG-32, IAEA, Vienna (2015).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Status of Radon Related Activities in Member States Participating in Technical Cooperation Projects in Europe, IAEA-TECDOC-1810, IAEA, Vienna (2017).

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

[6] INTERNATIONAL AGENCY FOR RESEARCH ON CANCER, Radiation: Volume 100D — A Review of Human Carcinogens, IARC, Lyon (2012).

[7] DARBY, S., et al., Radon in homes and risk of lung cancer: Collaborative analysis of individual data from 13 European case-control studies, Br. Med. J. **330** (2004) 223.

[8] HUNTER, N., MUIRHEAD, C., BOCHICCHIO, F., HAYLOCK, R., Calculation of lifetime lung cancer risks associated with radon exposure, based on various models and exposure scenarios, J. Radiol. Prot. **35** 9 (2015) 539.

[9] WRIXON, A.D., et al., Natural Radiation Exposure in UK Dwellings, Rep. NRPB-R190, National Radiological Protection Board, Chilton (1988).

[10] REES, D.M., BRADLEY, E.J., GREEN, B.M.R., Radon in Homes in England and Wales — 2010 Data Review, Rep. HPA-CRCE-015, National Radiological Protection Board, Chilton (2011).

[11] ZEEB, H., Survey on Radon Guidelines, Programmes and Activities, World Health Organization, Geneva (2007).

[12] SYNNOTT, H., FENTON, D., An Evaluation of Radon Reference Levels and Radon Measurement Techniques and Protocols in European Countries, Radiological Protection Institute of Ireland, Dublin (2005).

[13] EUROPEAN COMMISSION, Council Directive 2013/59/EURATOM of 5 December 2013 Laying Down Basic Safety Standards for Protection Against the Dangers Arising from Exposure to Ionising Radiation and Repealing Directives 89/618/EURATOM, 90/641/EURATOM, 96/29/EURATOM, 97/43/EURATOM and 2003/122/EURATOM, EC, Brussels (2014).

[14] OTTON, J.K., The Geology of Radon, US Govt Printing Office, Denver, CO (1992).

[15] CAVALLO, A., GADSBY, K., REDDY, T.A., Comparison of natural and forced ventilation for radon mitigation in houses, Environ. Int. **22** Suppl. 1 (1996) S1073–S1078.

[16] CHEN, J., BLISS, T., ZIELINSKI, J., MOIR, D., Determining the sample size required for a community radon survey, Health Phys. **94** (2008) 362–365.

[17] FRIEDMANN, H., et al., The uncertainty in the radon hazard classification of areas as a function of the number of measurements, J. Environ. Radioact. **173** (2017) 6–10.

[18] ANTIGNANI, S., et al., An affordable proxy of representative national survey on radon concentration in dwellings: Design, organisation and preliminary evaluation of representativeness, Radiat. Meas. **50** (2013) 136–140.

[19] BURKE, O., MURPHY, P., The use of volunteer radon measurements for radon mapping purposes: An examination of sampling bias issues, J. Radiol. Prot. **31** (2011) 319–328.

[20] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement of Radioactivity in the Environment — Air: Radon-222 — Part 1: Origins of Radon and Its Short-Lived Decay Products and Associated Measurement Methods, ISO 11665:2012, ISO, Geneva (2012).

[21] CHEN, J., MOIR, D., A study on the thoron sensitivity of radon detectors available to Canadians, J. Radiol. Prot. **32** (2012) 419–425.

[22] FRANCI, D., AURELI, T., CARDELLINI, F., Study of ageing and fading in CR-39 detectors for different storage conditions, Radiat. Prot. Dosim. **167** (2014) 425–428.

[23] GUNNING, G.A., MURRAY, N., LONG, S.C., FOLEY, M.J., FINCH, E.C., Intercomparison of radon detectors for one to four week measurement periods, J. Radiol. Prot. **36** (2016) 104–116.

[24] BURKE, O., et al., Estimation of seasonal correction factors through Fourier decomposition analysis: A new model for indoor radon levels in Irish homes, J. Radiol. Prot. **30** (2010) 433–443.

[25] HEALTH CANADA, Guide for Radon Measurements in Residential Dwellings (Homes), Health Canada, Ottawa (2017).

[26] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, Protocols for Radon and Radon Decay Product Measurements in Homes, US EPA, Washington, DC (1993).

[27] ENVIRONMENTAL PROTECTION AGENCY, Advice to Local Authorities on Implementing a Radon Measurement Programme (2019), http://www.epa.ie/pubs/advice/radiation/radonadvicetolocalauthorities.html

[28] DARAKTCHIEVA, Z., MILES, J.C., McCOLL, N., Radon, the lognormal distribution and deviation from it, J. Radiol. Prot. **34** (2014) 183–190.

[29] CINELLI, G., TONDEUR, F., Log-normality of indoor radon data in the Walloon region of Belgium, J. Environ. Radioact. **143** (2015) 100–109.

[30] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, The 2007 Recommendations of the International Commission on Radiological Protection, Publication 103, Sage, Thousand Oaks, CA (2007).

[31] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Lung Cancer Risk from Radon and Progeny and Statement on Radon, Publication 115, Sage, Thousand Oaks, CA (2010).

[32] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Radiological Protection against Radon Exposure, Publication 126, Sage, Thousand Oaks, CA (2014).

[33] GRUBER, V., RINGER, W., WURM, G., FRIEDMANN, H., Radon mapping strategies in Austria, Radiat. Prot. Dosim. **167** (2015) 65–69.

[34] FENNELL, S.G., et al., Radon in Dwellings: The Irish National Radon Survey, Radiological Protection Institute of Ireland, Dublin (2002).

[35] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, EPA Map of Radon Zones, US EPA, Washington, DC (2015), https://www.epa.gov/sites/production/files/2015-07/documents/zonemapcolor.pdf

[36] PUBLIC HEALTH ENGLAND, Radon Information for Householders (2018), http://www.ukradon.org/sectors/householders

[37] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, National Radon Control Strategy: Householders (2017), http://www.epa.ie/radon/householders/

[38] INTERNATIONAL ATOMIC ENERGY AGENCY, A Flowchart for the Development of a National Radon Action Plan (RAP), IAEA, Vienna (2017).

[39] INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR OFFICE, Occupational Radiation Protection, IAEA Safety Standards Series No. GSG-7, IAEA, Vienna (2018).

[40] BECK, T.R., FOERSTER, E., BUCHROEDER, H., SCHMIDT, V., DOERING, J., The measurement accuracy of passive radon instruments, Radiat. Prot. Dosim. **158** (2014) 59–67.

[41] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, General Requirements for the Competence of Testing and Calibration Laboratories, ISO/IEC 17025:2017, ISO, Geneva (2017).

[42] INTERNATIONAL ATOMIC ENERGY AGENCY, National and Regional Surveys of Radon Concentration in Dwellings: Review of Methodology and Measurement Techniques, IAEA Analytical Quality in Nuclear Applications Series No. 33, IAEA, Vienna (2013).

[43] HEALTH CANADA, Cross-Canada Survey of Radon Concentrations in Homes: Final Report, Health Canada, Ottawa (2012).

## Annex I

## NATIONAL RADON SURVEY IN ARGENTINA

In 1983, Argentina's Autoridad Regulatoria Nuclear (ARN) initiated a national radon survey, which was carried out on a phased basis over several years, until 2011. The main reason for undertaking the survey was to identify areas of the country with elevated radon concentrations. In the 1980s, a clear relationship between residential exposure due to radon and lung cancer risk had not yet been demonstrated.

Higher concentrations of radon were found in connection with some cases of occupational exposure, so it was important from the point of view of radiation protection to know whether there were areas of the country with elevated radon concentrations.

A second objective was later added: to assess the average radiation dose and the range of radiation doses received by the Argentine population due to radon, for comparison with doses due to other sources of radiation, as radon is the main natural source for radiation exposure of the public.

As for areas of potentially elevated radon concentrations indoors, Argentina has a number of locations where uranium was previously mined, which raises the likelihood of radon being present. Uranium was mined mainly by means of open pit technology and a lixiviation (leaching or dissolving) process, and at a few locations by underground mining. The mineral was present in low grade deposits.

All uranium mining activities ended in 1997 and the majority of the uranium mines are closed. One uranium mining facility could potentially be reopened, but it is not currently operating. All of these old mine areas are controlled through regulation and monitoring by the ARN.

As described above, the initial objective of the residential radon survey was to identify areas of the country with elevated radon concentrations. However, the project was later oriented with the regulatory objective of assessing the exposure of members of the public whose dwellings are in the surroundings of the uranium mining facilities, as radon gas is the main radiological hazard associated with these sites.

Argentina has adopted an annual average radon concentration of 400 Bq/m$^3$ as the national reference level above which corrective actions to reduce radon concentrations in dwellings are to be considered [I–1]. ARN is in the process of revising its standards, and as part of this effort, the national reference level for radon will be revised and IAEA recommendations will be taken into account.

## I–1. NATIONAL DEMOGRAPHICS

Argentina is the eighth largest country in the world in terms of land area and the second largest in South America (after Brazil), with a surface area of 2.78 million $km^2$ [I–2]. In the mid-1980s the population was approximately 30 million; this had increased to 42.5 million by 2013 [I–3].

Over 90% of the population lives in urban areas. As estimated from the 2010 census, the population density ranges from 1.1 persons per $km^2$ in the province of Santa Cruz to over 14 000 persons per $km^2$ in the capital city, Buenos Aires [I–4].

The country is divided into 23 provinces and the autonomous capital of Buenos Aires. The provinces and the capital have their own constitutions under a federal system. The provinces are required to follow the national constitution but otherwise they are fully autonomous, managing their finances and owning their natural resources [I–5].

Because of its size, Argentina has great variability in climate. The northern regions have a tropical climate with high temperatures and high humidity over the summer months. In the southern parts of the province of Patagonia, though, the climate is subpolar.

## I–2. SURVEY DESIGN

The ARN decided to carry out radon measurements in 14 cities around the country selected to provide good coverage in terms of both land area and geology. This included the three cities with the highest populations: Buenos Aires, Cordoba and Rosario.

The survey started in dwellings near uranium mining and processing facilities regulated by ARN. Later, schools and universities were surveyed, in some cases working with local governments through municipal and provincial institutions.

Once contact with prospective participants was made by the local coordinator responsible for the distribution of detectors, the objective was to make the assignment of detectors as random as possible, while aiming to maximize the likelihood of detectors being recovered for analysis. Local coordinators or ARN personnel collected the detectors.

Each householder who volunteered to participate was provided with a questionnaire that included questions about the characteristics of the dwelling and the living habits of the occupants. At the end of the exposure period, the results obtained were sent out to each participant together with an explanation of what they meant.

Most of the measurements were carried out in family dwellings that were constructed predominantly from bricks and concrete, with a variety of ventilation systems.

As radon concentrations indoors vary owing to the weather and ventilation rates, the surveys were undertaken mainly using time integrated methods: passive track etch detectors (solid state nuclear track detectors) using Makrofol polycarbonate film and CR-39, with an exposure period of three months. Under these conditions, the lower limit of detection is approximately 10 Bq/m$^3$. The measurements were preferably performed in the winter.

Also, in a few cases, short term detectors (activated charcoal detectors and electret detectors) were used for the purpose of making initial screening measurements. During the development and calibration of the activated charcoal technique, the technique was checked in parallel with the electret detector technique in Buenos Aires city [I–6]. These short term measurements were performed with the objective of identifying dwellings with increased radon concentrations in a short time (3–7 days). Long term measurements were then performed to assess representative averages.

All radon detectors were analysed at ARN laboratories in Buenos Aires. The detectors were calibrated and verified using a reference chamber in which the concentrations of radon and radon progeny could be controlled. Moreover, ARN participates in several intercomparison exercises as part of the quality assurance and quality control programme.

## I–3. RESULTS AND ANALYSIS

Up to 2011, 3170 passive measurements were carried out in the 14 selected cities. The highest number of dwellings tested in a province was 1284 in Mendoza province (a uraniferous area). In the province of Buenos Aires, the province with the highest population, 464 measurements were carried out.

The average radon concentration, with all the measurements taken into account, is 46 Bq/m$^3$, with a maximum value of 627 Bq/m$^3$ [I–7 to I–9]. Of the completed measurements, very few exceeded 200 Bq/m$^3$, and only two results exceeded 300 Bq/m$^3$.

Also, a specific survey was performed in several cities with a passive track etch device, developed in ARN’s laboratory, to measure both the radon concentration and the equilibrium factor (a measure of how close radon is to equilibrium with its progeny) [I–10]. A total of 204 dwellings were measured, revealing an average radon concentration of 47.1 Bq/m$^3$ in this specific survey, with an average equilibrium factor of 0.36. The average radon concentration was in good agreement with the results of the main survey.

Radon gas levels are low in Argentina, mainly because dwellings are well ventilated and because geologically, a majority of the ground is sedimentary.

## I–4. FOLLOW-UP ACTIONS

Owing to the generally low concentrations measured in the radon survey, no follow-up actions were considered necessary.

## I–5. POST-SURVEY CONSIDERATIONS

When the radon survey was begun in 1983, its objectives were different from those in place when it was completed in 2011. This complicated the situation, together with other issues such as having only a limited number of detectors available and not always being able to find a reliable local coordinator to distribute the detectors. For these reasons, the survey was not as random and representative as desired.

Measurements in uranium mining areas were repeated throughout the years for the same dwellings in many cases. As a result, average provincial and national results for radon concentrations may be biased.

In order to improve the surveys, it is desirable that one of two survey approaches be taken first, instead of aiming for two objectives at once:

(a) Estimate the average radon concentration in the country (or in some region of the country) in order to estimate the exposure of the population, basically by making a distribution of the measurements according to the population in each city (or in any given area);
(b) Locate radon prone areas by dividing the country (or some region within the country) according to geological criteria (related as closely as possible to expected radon concentrations indoors), and allocating measurements randomly within the selected areas.

For estimating the exposure of the population, using measurements made in winter alone seems to be adequate (some conservativeness introduced thereby is preferable to raising the costs with more measurements). For locating radon prone areas, variability in climate in the country may also need to be taken into account, so it is not yet clear whether studies need to be done in other seasons.

The handling of information, especially data on construction materials, type of flooring, number of windows in dwellings, and so on, should be given serious consideration, since introducing it into databases can be very time consuming and may be left incomplete. On the basis of past experience in Argentina, correlations among the characteristics of dwellings and radon concentrations could not be investigated for this reason.

## REFERENCES TO ANNEX I


[I–1] AUTORIDAD REGULATORIA NUCLEAR, Norma Básica de Seguridad Radiológica, AR.10.1.1 Rev. 3, ARN, Buenos Aires (2016).

[I–2] WORLD BANK, Argentina Surface Area (sq. km) 1961–2015 (2016), http://data.worldbank.org/indicator/AG.SRF.TOTL.K2?locations=AR

[I–3] WORLD BANK, Argentina Population Total 1960–2015 (2016), http://data.worldbank.org/indicator/SP.POP.TOTL?locations=AR

[I–4] ARGENTINA CENSUS, Mapas Temáticos Censo (GEOCENSO) (2010), http://200.51.91.231/censo2010/

[I–5] UNITED NATIONS, Republic of Argentina: Public Administration Country Profile, UN, New York (2004).

[I–6] CANOBA, A.C., LÓPEZ, F.O., OLIVEIRA, A.A., Radon determination by activated charcoal adsorption and liquid scintillation measurement, J. Radioanal. Nucl. Chem. **240** 1 (1999) 237–241.

[I–7] CANOBA, A.C., et al., "Mediciones de gas radon en el interior de viviendas de la República Argentina", Proc. Fifth Regional Congress on Radiation Protection and Safety, Iberian and Latin American Congress of Radiological Protection Societies, Regional International Radiation Protection Association (IRPA) Congress, Recife, 2001, Sociedade Brasileira de Proteção Radiológica, Recife (2001).

[I–8] CANOBA, C., et al., Indoor radon measurements in six Latin American countries, Geofis. Int. **41** (2002) 453–457.

[I–9] BONETTO, J.P., CANOBA, A.C., LOPEZ, F., "Radon measurements in Argentina", Latin American Symp. Radon, Second Seminar on Radon in Brazil, Pocos De Caldas, 2014, Autoridad Regulatoria Nuclear, Buenos Aires (2014).

[I–10] LOPEZ, F.O., CANOBA, A.C., Passive method for the determination of the equilibrium factor be-tween $^{222}Rn$ gas and its short period progeny, J. Radioanal. Nucl. Chem. **258** 2 (2003) 269–274.

## Annex II

## NATIONAL RADON SURVEY IN AUSTRALIA

A population weighted radon survey was carried out in Australia with the aim of calculating dose rates for the population from exposure due to radon and exposure to gamma radiation. The measurements were taken over the period from September 1987 to July 1988. The detectors were returned to the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) for reading and analysis from September 1988 to September 1989, and the analysis was completed for publication in 1991 [II–1].

In general, the mean radon concentrations were quite low (annual average radon concentration of 12 Bq/m$^3$).

Three previous limited radon measurements that were performed in 1984, 1986 and 1988 show higher values than those of the 1991 survey; however, these three studies were not intended to be statistically representative of Australian dwellings. They used short integration periods of up to ten days with charcoal detectors, so there may have been discrepancies due to seasonal variations. Also, the population groups were chosen for convenience rather than for being representative of the whole population.

The calculations for dose from exposure due to radon concentrations indoors were obtained from Ref. [II–2], which showed that 1 mSv effective dose equivalent is received from every 20 Bq/m$^3$ of radon indoors. A correction factor is used to calculate the dose equivalent for children under five years old, owing to different breathing rates and the dimensions of the airways. These calculations were performed by assuming 24 hour occupancy of the dwelling; the doses may therefore be an overestimation.

### II–1. NATIONAL DEMOGRAPHICS

In 1991 Australia had a population of approximately 17.3 million and had approximately 5.8 million households, averaging just under 3 persons per household [II–3]. A large majority of the dwellings are separate, single family dwellings.

Administratively, the country is divided into six states, each of which has its own constitution and has the same divisions of legislature, executive and judiciary as the federal government. Two mainland territories were also included in the study: the Australian Capital Territory and the Northern Territory.

The analysis was performed on a statewide basis, and no grid system was used.

## II–2. SURVEY DESIGN

A total of 12 073 householders were selected randomly from the Australian electoral rolls and 3862 responded positively (~32% positive response rate). One dosimeter was sent out to each respondent. At the end of the study, 3416 dosimeters were returned.

Questionnaires were sent to each participant, together with an integrating dosimeter to measure both radon concentrations and gamma radiation, to be placed in the living area of the dwellings. The dosimeter was to be returned to the laboratory after 12 months for processing and analysis.

Prior to carrying out the national survey, a pilot survey was conducted to accomplish three things: (a) to make sure that the questionnaire was not too difficult, (b) to show that measurement techniques were sufficiently sensitive and (c) to estimate the percentage of recipients likely to participate in the survey. The measurement period for the pilot survey was three months, and 200 people were randomly selected for it from two urban divisions and one rural division near Melbourne. Of those, 60 responded positively (30% positive response rate).

The detectors used for radon detection were CR-39s. After 12 months of exposure, the detectors were etched with a 6.25M sodium hydroxide solution and manually read using an optical microscope. The detectors were calibrated in a radon chamber with a concentration of 4000 Bq/m$^3$.

The detectors used for gamma radiation contained dysprosium doped calcium sulphate incorporated into a Teflon disc as a thermoluminescent dosimeter. The Teflon disc was inserted between two foam discs at the bottom of a polypropylene jar. Prior to being used in the survey, the discs were calibrated with a known dose from exposure to $^{137}$Cs to check their compliance with the sensitivity criterion. Each disc was annealed for no more than two days before the detectors were dispatched, and the dose was determined using a Pitman 'Toledo' thermoluminescent dosimeter reader as soon as possible after receiving the discs following an exposure of 12 months.

## II–3. RESULTS AND ANALYSIS

### II–3.1. Radon

A total of 3413 observations were made; the geometric mean concentration of these was 8.7 Bq/m$^3$, while the arithmetic average concentration was 11.6 Bq/m$^3$.

In the questionnaire, there were many questions about possible factors for radon in the dwelling. The data then formed the basis for a multiple regression study using those factors. It was shown that all of the following are significant factors for the radon concentration: the state in which the dwelling is located, the materials used for the inner walls, the materials used for the outer walls, the nature of the underfloor space and how the dwelling is ventilated.

The results of the analysis showed that:

— Dwellings with brick or plaster and brick inner walls showed measurement results for radon concentrations that were about 30% higher than those for dwellings with timber walls.
— Dwellings with brick outer walls showed measurement results that were about 10% higher than those for dwellings with timber walls.
— Dwellings that use air-conditioning or wall vents alone for ventilation returned radon concentrations 15–25% higher than those for dwellings using windows or an external door for ventilation.
— Dwellings standing on the ground had radon concentrations in general 30% higher than those for dwellings raised off the ground on supports.

This analysis was performed for each state. It was found that no factor dominates across all states, and that dwellings built on supports in Western Australia, Victoria and Queensland have lower concentrations of radon on average, while dwellings in New South Wales and South Australia with brick inner walls have higher radon concentrations on average.

### II–3.2. Gamma radiation

For 3363 gamma observations made, the geometric mean gamma radiation dose was 854 μSv/a and the arithmetic average dose was 900 μSv/a. A multiple regression analysis was undertaken with many factors considered, and the following results were found:

— Exposure to gamma radiation changes according to the state. The highest average exposures were found in the Australian Capital Territory and Western Australia, and the lowest were received in the Northern Territory, Queensland and Tasmania.
— The type of dwelling does not contribute to differences in gamma radiation exposure.
— In general, dwellings built before 1944 are associated with elevated exposure to gamma radiation.
— In general, dwellings built with brick or plaster and brick inner walls are subject to about 25% higher levels of gamma radiation than those with wood or plaster inner walls.

— In general, dwellings with brick outer walls are subject to about 20% higher gamma radiation levels than those with timber or cladding outer walls.

The regression analysis was performed later on a state by state basis and it was found that the last two factors are consistently important. Also, the year of construction was an important factor only for dwellings built in New South Wales.

### II–3.3. Radiation dose

As mentioned previously, the dose estimates are based on Ref. [II–2], which showed that average exposure at a level of 20 Bq/m$^3$ leads to an effective dose equivalent of 1 mSv for adults and children over 5 years old, and 1.6 mSv for children under 5 years old. These calculations are based on a 24 hour occupancy of the dwelling by residents.

By using these conversion factors and the populations of the states, and from the annual average effective dose equivalent of 0.6 mSv from exposure due to radon, a ‘collective dose’ of $9.2 \times 10^3$ person-sieverts to the population of Australia from exposure due to radon was estimated.

For gamma exposure, the annual average effective dose equivalent of 0.9 mSv was used to estimate an annual ‘collective dose’ to the population for gamma exposure of $1.5 \times 10^4$ person-sieverts.

## II–4. FOLLOW-UP ACTIONS

In view of the low average radon concentration in Australia, it was decided that there is little cause for concern. Radon concentrations in only two of the 3413 dwellings surveyed exceeded the United Kingdom National Radiological Protection Board (part of Public Health England since 2013) action level of 200 Bq/m$^3$. This means that if the proportion is representative of the country as a whole, then only 2000–3000 dwellings across the country would have levels of radon in excess of this action level.

In Australia, each state and territory is responsible for regulating radiation protection within its jurisdiction. So, for the cases of dwellings where radon levels measured above the action level, ARPANSA recommends that the radiation health authority of the appropriate state or territory, or of the Commonwealth, be contacted for advice on remediation.

Further work was planned to identify the factors that contribute to the highest radon concentrations, but in view of the relatively low levels found in the 1991 study, the work was not given a high priority.

A new interactive version of the radon map was published in 2014. The results from the survey have been previously reported in a map based on postcode districts. This map has now been updated to provide district average levels for radon based on the Statistical Areas Level 2[1] regions from the 2011 Australian census.

The new interactive radon map displays interpolated values in census districts for typical Australian dwellings. While factors such as dwelling type, construction materials used and type of ventilation can affect the radon levels, the effects of these factors are small relative to effects due to the local geology and soil type. With account taken of the dwelling type, the actual radon levels in a particular dwelling may differ by a factor of up to two from the level shown on the map.

The new radon map shows that average radon levels in dwellings along the Great Dividing Range are typically higher than levels in dwellings on the coastal plain, mainly owing to differences in the nature of the underlying geology (rock and soil). This leaves scope for the development and publication of a true radon potential map for Australia, on the basis of geological considerations.

A follow-up targeted radon survey for selected dwellings in Victoria was undertaken in 2017–2018. This survey was conducted in conjunction with Sustainability Victoria. The study was aimed at dwellings due to undergo a government retrofit under a programme for household energy efficiency.

The radon levels in a selection of dwellings will be monitored with the aim of determining whether the retrofit programme affects radon concentrations in a positive or negative way. Recent studies in Europe [II–4] have shown that on average, dwellings that undergo thermal retrofits of this type have higher radon levels than before, although the construction material used has been shown to be the largest determining factor.

## II–5. POST-SURVEY CONSIDERATIONS

The key points that worked well are:

— The survey used the census data to provide a truly representative sample of the population(s).

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[1] Statistical Areas Level 2 (SA2) are medium sized general purpose areas. Their purpose is to represent a community that interacts together socially and economically. There are 2310 SA2 regions covering the whole of Australia without gaps or overlaps.

— The survey was conducted shortly after participation in IAEA intercomparison exercises, so there was a high degree of confidence that the results were accurate.
— The radon and gamma radiation detectors were placed in the living areas of the dwellings, so the results were a measure of actual exposure, not of potential exposures in basements.
— The instruments were in place for a full year, so the results were a true measure of annual exposure, with no seasonal bias.

The key issues encountered were:

— The project was not sufficiently well resourced; this resulted in long delays between measurements and publication and follow-up.
— The project was not always managed in a timely manner; again, this caused delays between measurement and publication.

## REFERENCES TO ANNEX II

[II–1] LANGROO, M.K., WISE, K.N., DUGGLEBY, J.C., KOTLER, L.H., A nationwide survey of $^{222}$Rn and $\gamma$ radiation levels in Australian homes, Health Phys. **61** 6 (1991) 753–761.

[II–2] NAZAROFF, W.W., NERO, A.V., Jr. (Eds), Radon and Its Decay Products in Indoor Air, Wiley, New York (1988).

[II–3] CASTLES, I., Census of Population and Housing 6 August 1991: Australia in Profile, Australian Bureau of Statistics, Canberra (1993).

[II–4] COLLIGNAN, B., LE PONNER, E., MANDIN, C., Relationships between indoor radon concentrations, thermal retrofit and dwelling characteristics, J. Environ. Radioact. **165** (2016) 124–130.

## Annex III

## NATIONAL RADON SURVEY IN AUSTRIA

A national radon survey was conducted in Austria from 1992 to 2001 with the aim of identifying high radon areas for targeted actions to reduce radon exposure in these areas. Previous geological investigations had not accurately estimated radon exposure in Austria, so it was decided to perform systematic measurements of radon indoors.

In 1992 the Austrian Radon Protection Commission recommended that the annual mean radon concentration in existing buildings should be no more than 400 Bq/m$^3$, and that it should be no more than 200 Bq/m$^3$ in new buildings [III–1].

### III–1. NATIONAL DEMOGRAPHICS

Austria has a surface area of 83 879 km$^2$ [III–2]. It was divided into a four tiered administrative structure as of the time of the survey: the federal government, nine federal provinces, 99 districts (sometimes referred to as counties) within the provinces, and 2358 local, self-administered municipalities.

The population grew from 7.8 million to about 8 million people from 1992 to 2001, and the number of households grew from about 3 million to about 3.2 million. There was an average of 2.6 persons per household in 1992 and 2.45 persons per household in 2001 [III–3, III–4].

### III–2. SURVEY DESIGN

For reasons of availability, only passive measuring systems were used, and only $^{222}$Rn was measured.

The survey was population based: dwellings were selected at random from the telephone directory so that the number of measurements in an area was proportional to the number of inhabitants. This was done to avoid over-representation of sparsely inhabited areas. One in every 200 dwellings was selected from the sample, and in the event of refusal to participate, another dwelling was selected (quasi-) randomly. Sample sizes were reduced in larger cities by concentrating on ground floor dwellings.

A three step approach to the national survey was taken. First, all data possibly relevant to radon concentrations indoors were gathered (e.g. existing data on radon indoors, uranium and thorium content in soil and rock, gamma dose measurement). Second, indoor measurements were performed on a test area in a rural environment and an urban environment. Then procedures were adjusted, such as methods of distribution of detectors, the timing of the project and the comprehensibility of the questionnaire. Locations were tested again in an extended pilot phase. Finally, the countrywide investigation began in 1994.

Three detector systems were utilized: solid state nuclear track detectors (SSNTDs), electrets and charcoal detectors with liquid scintillation counting measurement. One type of detector system was used for every municipality, and all three types were used in each district and province. Two detectors were placed in each dwelling in the most frequently used rooms (mainly the living room and a bedroom), one to two metres from the floor, and away from vents, windows and doors. Questionnaires were distributed together with the detectors to obtain information about the type of dwelling and the living conditions. Detectors and questionnaires were distributed either by interviewers or by mail.

The SSNTDs and electrets were used to perform three-month measurements, and the charcoal detectors were used for three-day measurements. All measurements were made in spring and autumn, under the occupants' normal living conditions (e.g. occupants were not asked to keep windows closed throughout the entire time).

The contribution of thoron was evaluated in representative dwellings in an area with relatively high thorium concentrations compared with other parts of Austria. It was concluded that the contribution of thoron to the effective dose can be ignored in most cases in Austria.

For administrative purposes, results were summed up on the basis of municipalities. The results were shown as arithmetic mean radon concentrations, resulting in a map that does not convey the range of values for each municipality.

## III–3. RESULTS AND ANALYSIS

'Radon potential' in this study is defined as the annual arithmetic mean radon concentration in a standard situation. A standard situation describes a single family dwelling (not a weekend house) with a living room on the ground floor, no basement or only a partial basement, no natural stone construction and no single paned windows, and inhabited by two adults and no more than one child. This standard situation was derived by analysing the questionnaires from the dwellings measured together with the observed radon concentrations.

Arithmetic mean conversion factors were deduced by comparing the density distribution function of the radon concentrations in groups that differed only in one parameter (e.g. with and without a basement). These mean conversion values were then used to renormalize all measured data to radon concentrations in the standard situation. The average of these renormalized data within a municipality then defined the radon potential for the municipality.

During the measurement process, approximately 40 000 measurements were performed in 8000 dwellings, representing 0.25% of the national housing stock of 3.2 million households. The rate of retrieval was approximately 85%. Among the approximately 2300 municipalities, this meant that there were measurements made in only about three to four dwellings each, on average.

No detailed information can therefore be given regarding different geological zones within a municipality. Only the mean radon concentration per municipality was computed, including corrections for the annual variation (by using derived seasonal correction factors). The mean radon concentration for Austria was found to be 99 Bq/m$^3$ [III–1]. A radon potential map was produced grouping municipalities into three categories: annual mean below 200 Bq/m$^3$, between 200 and 400 Bq/m$^3$, and above 400 Bq/m$^3$.

Many quality assurance and quality control measures were taken to avoid errors and to reduce uncertainties, but also to help estimate the contribution of certain quantities to the final uncertainty. Some of these measures include: random checks comparing questionnaires to census data, intercalibration and intercomparison between laboratories with different detector systems using a radon chamber, comparison of parallel measurements with different detector systems in the same dwellings, and comparison of the density distribution of the results from different detector systems in the same area.

High radon concentrations were commonly found in the Bohemian Massif and the Central Alps, owing to higher uranium concentrations in crystalline rocks. The observed radon concentrations are related to the geological make-up of the underlying rock, however. For example, in the high radon area of the Bohemian Massif, there are strongly weathered granitoids (with high gas permeability), and there are much lower radon levels in areas with more compact granitoids.

Nevertheless, the measured concentration in dwellings does not necessarily reflect geological circumstances, but depends on many other factors. Observed values for radon levels indoors are therefore only an indication of the geological situation.

## III–4. FOLLOW-UP ACTIONS

Currently, Austria is conducting another national radon survey to improve the reliability of the radon map (radon classification of municipalities) and to reduce the uncertainties, since with the application of the European basic safety standards [III–5], several decisions about measures to be taken will be based on the radon map (e.g. mandatory radon measurements at workplaces as well as preventive measures).

The first national radon survey was conducted on a population weighted basis. The current survey is geographically based, and is being undertaken specifically to create a radon map. About 35 000 measurements of radon indoors will be conducted in Austria, with passive detectors for six months (half in wintertime, half in summertime) in the two most heavily used rooms at ground level in dwellings.

The radon measurements will be selected on the basis of a 2 km × 2 km regular grid (European Terrestrial Reference System 1989 — Lambert azimuthal equal-area projection (ETRS-LAEA)) for a regular geographical distribution. The aim is to have at least one measurement point per grid cell (if geology is diverse) and one dwelling per geological unit (1:500 000) in each grid cell.

In addition, a minimum of 12 dwellings per municipality is required. The number of at least 12 dwellings is a compromise between available financial means and acceptable uncertainty in the characterization of the radon related risks in a municipality [III–6].

The measurements are carried out in the dwellings of members of voluntary fire brigades. The voluntary fire brigades in Austria have about 300 000 members, who, it is expected, will cover all social and occupational backgrounds, all age groups and all housing situations. The advantage is that a high return rate is expected, as these are motivated persons and they are part of a hierarchical organization.

The distribution of detectors is done by the local fire brigade chiefs. More details are reported in Ref. [III–7]. Together with the measurements, information about the characteristics of dwellings is collected (by questionnaire) and the dependence of the radon concentration on relevant factors is modelled. For the map, a standard radon potential can be predicted for a reference dwelling for the defined basis (grid cell, geological unit and municipality). A new map should be completed by 2019.

## III–5. POST-SURVEY CONSIDERATIONS

The first Austrian national radon survey was done according to the technical and administrative resources available at that time and yielded good results for the main goals that were set: evaluation of the average radon concentration levels for the population and identification of regions with high radon potential. For the new challenges, a more reliable radon map is required, and some of the uncertainties of the first national radon survey need to be reduced.

The first national survey included short term measurements (using charcoal detectors, for several days). Even if comparison measurements were conducted, and it was determined that short term measurements can be used if accuracy for only an area (municipality) is needed, misclassification of municipalities that are assessed only with short term measurements is quite likely. Also, the use of different measurement systems is a source of uncertainty, as is the calculation of an annual mean from the measurements made (short term, up to three months) by using seasonal correction factors.

The number of dwellings measured per municipality was on average three to five, and variation of the radon potential within the municipality (due to its geology) was not taken into account. To reduce or to avoid the sources of uncertainty, the new survey is carried out with only one measurement system for six months (half wintertime, half summertime), without applying a seasonal correction factor, in selected dwellings according to a grid cell (taking into account geology) in at least 12 dwellings per municipality.

The dwellings in the first national survey were selected using the telephone directory with a fixed step size to ensure that the measurement density was proportional to the population density. This was a good selection method at that time, but it would not be possible today, as landlines are sparse and most mobile phones are not listed in a telephone directory. A new method for the selection of dwellings therefore had to be found for the new survey: dwellings of fire brigade members. To test the representativeness of the sample, the questionnaire included several questions identical to those used in the last national census. It was found that the sample was not biased.

The distribution of detectors was mainly done by paid interviewers. The success rate was very high in general, but was of course dependent on the individual interviewer. A crucial point is to train and inform the interviewers appropriately about radon and the project.

The questionnaires that were filled out by the interviewers together with the participants had a higher quality than those in other surveys, which were only sent by post to the participants. When detectors are distributed by post, follow-up calls are suggested to support participants in the placement of detectors and completion of the questionnaire. The questionnaires were limited to one page with multiple choice questions, where possible, to simplify them for the participant, but also for the effective processing of the information afterwards.

For the national survey, local and regional politicians (mayors and members of government of the provinces) were informed or were involved in the project. This raises the acceptance by the participants and will be done again for the current survey. Also, involving local interviewers or other local people (in clubs, fire brigades, health services and so on) in the distribution of detectors helps to increase acceptance by the participants, and results in a higher return rate.

## REFERENCES TO ANNEX III


[III–1] FRIEDMANN, H., Final results of the Austrian radon project, Health Phys. **89** 4 (2005).

[III–2] WORLD BANK, Surface Area (sq. km) of Austria (2015), http://data.worldbank.org/indicator/EN.POP.DNST?end=2015&locations=AT&start=1961&view=chart

[III–3] STATISTICS AUSTRIA, Population since 1869 by Länder (2015), http://www.statistik.at/web_en/statistics/PeopleSociety/population/population_censuses_register_based_census_register_based_labour_market_statistics/totaL_population/028544.html

[III–4] STATISTICS AUSTRIA, Private Households 1985 to 2015 (2016), http://www.statistik.at/web_en/statistics/PeopleSociety/population/households_families_living_arrangements/households/032309.html

[III–5] EUROPEAN COMMISSION, Council Directive 2013/59/EURATOM of 5 December 2013 Laying Down Basic Safety Standards for Protection Against the Dangers Arising from Exposure to Ionizing Radiation, and Repealing Directives 89/618/EURATOM, 90/641/EURATOM, 96/29/EURATOM, 97/43/EURATOM and 2003/122/EURATOM, EC, Brussels (2014).

[III–6] FRIEDMANN, H., et al., The uncertainty in the radon hazard classification of areas as a function of the number of measurements, J. Environ. Radioact. **173** (2017) 6–10.

[III–7] GRUBER, V., RINGER, W., WURM, G., FRIEDMANN, H., Radon mapping strategies in Austria, Radiat. Prot. Dosim. **167** (2015) 65–69.

## Annex IV

## NATIONAL RADON SURVEY IN BULGARIA

In order to obtain the first systematic data for radon concentrations indoors, a pilot indoor radon survey was conducted in Bulgaria under a regional project of the IAEA (RER9094). The survey was performed during 2011 and 2012 in four districts: Sofia City, Sofia, Plovdiv and Varna. The main purpose was to check the protocols and organization for a national radon survey [IV–1].

Following this survey, an extensive population weighted national radon survey was conducted in Bulgaria from 2015 to 2016. The survey indicated that the likelihood of a dwelling having elevated radon concentrations indoors was greatest in the southern part of the country.

In 2012, the Government adopted radon reference levels in the Regulation on Basic Norms of Radiation Protection, which sets the basic standards for protecting the health of personnel and the population in Bulgaria from harmful effects of ionizing radiation. The national reference level was set to a radon concentration of 200 Bq/m$^3$ for new buildings and 300 Bq/m$^3$ for existing buildings (annually averaged), above which corrective measures are required to be applied [IV–2].

### IV–1. NATIONAL DEMOGRAPHICS

Bulgaria has a surface area of 111 000 km$^2$ [IV–3]. According to Eurostat's Classification of Territorial Units for Statistics in Bulgaria, the territory of the country is divided first into two statistical zones (northern and eastern Bulgaria, and south-western and south central Bulgaria). These two zones contain six statistical regions which in turn contain 28 districts. The smallest units are called local administrative units and are split into 264 municipalities and 5329 settlements.

The population in 2015 was 7.2 million and the population density was 65.3 per square kilometre. The total number of dwellings in Bulgaria is 3.9 million, of which 2.6 million are in towns and 1.3 million are in villages [IV–4].

### IV–2. SURVEY DESIGN

Passive measurement systems were used in the national survey, and only $^{222}$Rn was measured.

The survey was population based. The sample points were divided into 100 detectors per district according to a previously designed distribution scheme. A two stage stratified sampling scheme was used. The first stage included stratification of districts to 264 municipalities, which were then subdivided into the two strata of towns and villages. The number of detectors in each stratum was determined proportionally to the population density.

The survey was promoted and coordinated by Bulgaria's national laboratory (the National Centre of Radiobiology and Radiation Protection) and was carried out in collaboration with regional health inspectorates in two phases over one year. The dwellings were randomly selected by using a door to door approach for contacting families and distributing detectors. Survey participants received detectors together with instructions, and questionnaires were completed in interviews to obtain characteristics of dwellings.

Detectors were deployed on the ground floor and were swapped with new detectors for the second phase for a measurement period that totalled one year. The survey started in April 2015 and finished in approximately May/June 2016. The measurements were made under the occupants' normal living conditions. At the end of the survey period, the detectors were collected by the regional health inspectorates and were processed at the National Centre of Radiobiology and Radiation Protection.

The measurements were performed with passive track detectors (CR-39). Each detector contains two chips for providing the linearity of calibration. The main detector chip works with the main relative sensitivity factor type diffusion chamber.

The secondary chip works with a secondary diffusion chamber. If the upper limit of the linear calibration model is exceeded, the secondary chip is used for measurement of the radon concentration. The annual radon concentration for each dwelling was calculated as the weighted average of the results from the measurements of the two phases.

## IV–3. RESULTS AND ANALYSIS

The measurements were completed in 2775 dwellings. The detectors were distributed according to population, with 73% of dwellings being in urban environments and 27% in rural environments. The dwellings used for the measurements are masonry buildings with stone or reinforced concrete foundations. The detectors were placed in the rooms where people spend most of their time, often in the living room and in children's rooms or bedrooms. This information is taken from the questionnaires that were completed by residents.

The mean radon concentration was 111 Bq/m$^3$, with a maximum value of 1314 Bq/m$^3$. In 166 dwellings assessed, or about 6% of the total number, the radon concentration was found to be in excess of the reference value of 300 Bq/m$^3$ suggested by the European Commission in Council Directive 2013/59/EURATOM [IV–5]. The results will be aggregated on the basis of districts as mean radon concentrations for preliminary information on the radon potential.

High concentrations of radon are found in central and south-eastern Bulgaria. There are no mountains in most of the region's territory; the geology for the most part is lowland, but there are former uranium mining sites where in situ leaching technology was used. It is possible that materials from waste rock piles were used for the construction of buildings. This needs to be further explored during the follow-up radon surveys to identify radon prone areas.

Many quality assurance and quality control measures were taken to avoid errors and to reduce uncertainties, as well as to help estimate the contribution of certain quantities to the final uncertainty. Some of these measures included intercalibration and participation in international intercomparison between laboratories, and using 10% duplicated measurements and blank detectors.

The assessment of duplicate measurements for the first phase found that 93% of pairs have acceptable results and 7% have unacceptable results. For the second phase, the assessment was that 86% of pairs have acceptable results and 14% have unacceptable results. The results from both phases show that there is no loss of control (<20% unacceptable results of pairs was taken as the critical level for the whole set of measurements).

The annual effective dose from exposure due to radon in dwellings has been estimated to be 5.8 mSv using the preliminary International Commission on Radiological Protection dose coefficient of $7.5 \times 10^{-6}$ (mSv/h)/(Bq/m$^3$) and 7000 h occupancy per year.

## IV–4. FOLLOW-UP ACTIONS

Bulgaria is currently conducting a national radon survey for the analysis of regional seasonal variation. For the purposes of determining the correction factors as a result of seasonal variations, Bulgaria is divided into four regions depending on climate zone and geology. Measurements will be conducted in dwellings for the whole year, and the detectors will be changed every three months in accordance with the four seasons in Bulgaria.

Also, a pilot study is being conducted in one district in the north-west for checking the methodology for preparing the radon map of Bulgaria. For administrative purposes, the survey is organized on the basis of municipalities, and results will be summed up on the same basis.

For determining the number of detectors, a stratified sampling approach is used that is based on municipalities with a level of precision (accuracy) of 0.2, at 95% confidence limits. Thus the distribution of samples is homogeneous according to the area, but not homogeneous according to population density and housing stock in the municipality. For this, an additional weighting factor is used based on the percentage of the distribution of buildings in the municipality.

The number of detectors, in accordance with the methodology, is from 40 to 201 per municipality. The survey aims to cover the entire territory of each municipality in the district, and 1.5% to 1.9% of buildings will be covered. The period of measurement is three months during the spring. The distribution of detectors is carried out with the assistance of regional health inspectorates and mayors of municipalities through information days in the region. The detectors are placed in randomly selected dwellings or in the dwellings of volunteers from the villages.

Questionnaires about housing characteristics will be collected together with the measurement information, and the dependence of the radon concentration on relevant factors will be modelled. Analysis of the results and the method will allow protocols to be prepared for conducting measurements of the whole territory of Bulgaria and will allow the preparation of a radon map for Bulgaria.

An ordinance on technical standards for preventive measures and corrective actions for buildings is now being prepared.

Legislation in the field of radiation protection in Bulgaria through transposition of Directive 2013/59/EURATOM [IV–5] is in preparation.

## IV–5. POST-SURVEY CONSIDERATIONS

The first national radon survey for Bulgaria was carried out in accordance with the available technical and administrative resources. It yielded good results for the evaluation of average radon concentrations and preliminary results for identifying regions with high radon potential. For the new challenges, a radon map is required, and some of the uncertainties of the first national radon survey need to be reduced.

The dwellings in the first national survey and in the pilot survey were selected using a door to door approach through regional health inspectorates and mayors of municipalities. This was a good selection method, because personal communication helps to convey information better and helps to increase public awareness. Also, the questionnaires were completed by the interviewers together with the participants, so the information they provided was of better quality and was more thorough.

However, this method requires more time and effort, and requires training and informing the regional health inspectorates and mayors of municipalities appropriately about radon and the project, and how to perform the door to door approach.

It would therefore have been easier and more cost effective to use another method. This could have been similar to what was done in Austria, by having voluntary fire brigades distribute detectors and information, because voluntary fire brigades are organized in a hierarchical way (see Annex III). The questionnaires would be used for analysis and review, where possible — to simplify it for the participant, but also to process the information effectively afterwards.

For the national survey, local and regional politicians (e.g. mayors of municipalities) plan to be involved in the project. They will help disseminate information about the radon survey, contact potential participants, and allow the use of administrative buildings for organizing information days or for training.

Upgrades are planned for the national database with GPS coordinates of the dwellings assessed in order to allow the data to be better organized and compiled on a radon map that could be of greater benefit to local planning authorities.

## REFERENCES TO ANNEX IV


[IV–1] IVANOVA, K., STOJANOVSKA, Z., BADULIN, V., KUNOVSKA, B., Pilot survey of indoor radon in the dwellings of Bulgaria, Radiat. Prot. Dosim. **157** (2013) 594–599.

[IV–2] COUNCIL OF MINISTERS OF BULGARIA, Regulation on Basic Norms of Radiation Protection, State Gazette **76** (2012).

[IV–3] WORLD BANK, Surface Area (sq. km) of Bulgaria (2018), http://data.worldbank.org/indicator/AG.SRF.TOTL.K2?locations=BG

[IV–4] NATIONAL STATISTICAL INSTITUTE, Statistical Yearbook 2015, NSI, Sofia (2016).

[IV–5] EUROPEAN COMMISSION, Council Directive 2013/59/EURATOM of 5 December 2013 Laying Down Basic Safety Standards for Protection Against the Dangers Arising from Exposure to Ionizing Radiation, and Repealing Directives 89/618/EURATOM, 90/641/EURATOM, 96/29/EURATOM, 97/43/EURATOM and 2003/122/EURATOM, EC, Brussels (2014).

## Annex V

## NATIONAL RADON SURVEY IN CANADA

Between 1978 and 1980, Health Canada carried out a national survey of 13 500 dwellings in 18 cities across Canada [V–1]. The radon measurements made were all short term using instantaneous grab sampling. The survey predicted that approximately 5% of Canadians were living in dwellings with radon concentrations above 200 Bq/m$^3$. The survey also identified a number of areas where the radon concentrations indoors were higher than in other areas.

In the late 1980s, a large study of radon concentrations indoors was undertaken in the Winnipeg area [V–2]. The radon measurements were all long term and were made using passive integrating track etch detectors. Some smaller targeted studies were also carried out in other regions [V–3].

In 1988, Canada established a national radon 'guideline'[1] of 800 Bq/m$^3$. This was based on the scientific information available at the time. In 2007, with new information available and following a public consultation, the national radon 'guideline' level was reduced to 200 Bq/m$^3$ [V–1].

### V–1. NATIONAL DEMOGRAPHICS

Canada is the second largest country by land mass but only the 40th by population. It has a surface area of just under 10 million km$^2$ and the 2016 census quotes a population of 36 million.

Canada operates a federal system of government, with ten provinces and three territories. The territories lie primarily north of 60° latitude; they account for 40% of the land mass but only about 3% of the population. Provinces execute constitutional powers in their own right, but territories have traditionally been administered and managed by the federal government.

One of the delegated powers is for health care, implying that decisions in relation to exposure due to radon in dwellings are to be managed at the provincial level rather than the national level. Radon policies are established at the federal level and it is up to the provinces and territories to adopt and apply them within their health care system.

Canada is also divided into health regions, sometimes referred to as health authorities. These are administrative areas, defined by the provinces and

[1] The 'guideline' is a voluntary, non-regulatory level at which Health Canada recommends action to reduce radon concentrations indoors. As such, it is similar to an action level or reference level used in other countries.

territories, for the delivery of health care and public health initiatives. Health regions are the basic geographical unit by which health and health related statistics are collected. The number of health regions changes from time to time as regions are merged or are further subdivided.

## V–2. SURVEY DESIGN

Health Canada undertook the Cross-Canada Survey of Radon Concentrations in Homes over a period of two years, commencing in 2009. The survey was structured around the 2007 health regions. At the time there were 124 health regions, but for the purposes of the survey some of the less densely populated regions were amalgamated to give a total of 121 regions.

The main purposes of the survey were defined as: (a) estimating the proportion of the Canadian population living in dwellings with radon concentrations above 200 Bq/m$^3$; (b) identifying previously unknown areas where the exposure due to radon gas may constitute a health risk; and (c) over time, building a map of radon exposure.

The target was to complete 14 000 measurements in the two years. From reviewing information on previous surveys, it was expected that the number of completed measurements would be 75% to 80%. On that basis, it was decided to recruit 18 000 initial participants. The average number of participants to be recruited in each health region was therefore 149. However, the actual numbers were adjusted to reduce the number of participants in those regions where reliable long term measurement data were already available and to increase the number in areas for which there was little information.

In order to provide good geographical coverage, in rural health regions with a large urban centre, the goal was to recruit no more than 50% of the sample from that town or city. This goal was achieved in roughly 90% of the relevant health regions; in most others where it was not achieved, 50–60% of the sample came from that town or city.

A market research company was contracted to recruit participants for the survey and to follow up with them throughout the testing period. Participants were recruited by telephone: the telephone prefix gave a good indication of the location of the dwelling, while random digit dialling was used to contact individuals.

An additional restriction was that the survey could only include dwellings that were privately owned and occupied. Rental properties were excluded from the survey in order to obviate possible problems between landlords and tenants in the event that the result of the measurement of radon concentration levels exceeded the guideline level.

Dwellings that were built on stilts or that were located above the second floor of high rise buildings were excluded. Department of National Defence housing and First Nations housing was also excluded, since these dwellings were already covered or were expected to be covered in other surveys.

Approximately 200 000 telephone calls were necessary to recruit the 18 000 participants. Each participant was sent a radon detector by the National Radon Laboratory, together with instructions on its use and a zip bag and prepaid envelope for its return at the end of the measurement period. A questionnaire covering the age and type of construction of the dwelling, type of heating system, occupancy rates, tobacco smoking habits and the results of any previous radon measurements was also included.

All measurements were to be carried out for a minimum period of three months during the 'heating season' of October to March. This allowed detectors to be distributed on a phased basis. The contractor kept in touch with the participants during and at the end of the measurement period. Any items which were lost, such as the questionnaire or the prepaid envelope, were replaced by staff of the National Radon Laboratory. The programme was conducted in both English and French, the two official languages of Canada.

In the first year of the survey, the completion rate of measurements was 73%. On the basis of the experience gained by the market research company in its interactions with the participants and by staff of the National Radon Laboratory, some modifications were made to the administrative arrangements for the second year. The completion rate increased to 81%. The overall completion rate was 77%, in line with expectations when the survey was commenced.

## V–3. RESULTS AND ANALYSIS

The report of the survey [V–1] provides the percentage of dwellings exceeding the reference level in each province or territory and for each health region, but the results of the measurements of radon activity concentration carried out in each region are not given. In other documents and reports, the average radon concentration in Canadian dwellings is quoted as 96 Bq/m$^3$ [V–4].

The provinces and territories where radon levels are highest are Manitoba, New Brunswick, Saskatchewan and Yukon Territory. There were 14 health regions where about 20% to 40% of the dwellings tested had radon concentrations above 200 Bq/m$^3$, and a further nine health regions where the percentage of dwellings with levels above the guideline level was between 16% and 21%.

The data have been population weighted, and the results indicate that approximately 6.9% of the population is living in dwellings where the radon concentration exceeds 200 Bq/m$^3$, with 0.7% living in dwellings where the radon concentration exceeds 600 Bq/m$^3$.

## V–4. FOLLOW-UP ACTIONS

All participants were issued a results letter sent in the mail by the National Radon Laboratory. Where test results exceeded 200 Bq/m$^3$, the homeowner was also provided with general information on radon, including information on how to reduce radon concentrations. Homeowners were also advised that the higher the radon concentration, the sooner action needed to be taken [V–5].

At the time this national radon survey was carried out, there was already significant evidence that there were areas of the country where dwellings had elevated radon concentrations. Health Canada had therefore already developed a National Radon Program. The national radon survey was seen as an integral part of the National Radon Program and not a precursor to it.

In 2012 and 2013, Health Canada undertook a national survey involving concurrent long term radon and thoron measurements [V–4]. Measurements were completed in over 3000 dwellings across Canada. The average population weighted radon concentration measured was 96 Bq/m$^3$ and the average for $^{220}$Rn was 9 Bq/m$^3$. About half of dwellings had $^{220}$Rn concentrations below the detection limit of 4 Bq/m$^3$.

By applying the relevant dose conversion factors, it was concluded that the dose from exposure due to thoron is about 3% of that due to radon. The results also show no correlation between the measured radon concentrations and $^{220}$Rn concentrations in individual dwellings.

Work is continuing to develop a mapping methodology for the radon potential in Canada [V–6].

Data from Health Canada's radon testing projects, as well as aerial and land radiation surveys and provincial geological surveys, are being used in the development of possible methodologies for studying radon rich areas across Canada.

The data from these surveys have been used in many jurisdictions to help bring about further changes in building codes in order to protect the population from radon indoors, and to support other possible policy changes (such as changes in labour codes), and in radon related research.

The National Radon Program established a certification programme for professionals in radon measurement and remediation (the Canadian National Radon Proficiency Program). The National Radon Program continues to conduct research on radon measurement and remediation, has sponsored publication of one national standard for remediation, and continues to work on national standards and to conduct outreach to Canadians regarding the need to test their dwellings for radon and to remediate them where necessary to reduce the risk of radon induced lung cancer.

## V–5. POST-SURVEY CONSIDERATIONS

The overall administrative burden of carrying out the survey was underestimated. While the recruitment of participants and the mailing of test kits were effectively organized, much time was spent on meeting the need for follow-up and reminder calls. Providing additional materials to some participants added to the workload.

Despite the efforts made to ensure that the instructions were simple, some homeowners were unable to follow them. This was not foreseen and evidently a short YouTube-type on-line instructional video on how to place the detectors would have been helpful.

It would be ideal if participants could enter their deployment and collection data (e.g. test start and end dates) and information for the questionnaire on housing characteristics via an on-line portal. That would save a great deal of time and would also make analysis of data from the questionnaire much easier.

Reminders to return detectors could be sent via a general email distribution. In smaller, more recent surveys, Health Canada has followed up directly by email with participants in the testing, and it has been quite successful.

With hindsight, it might have been better to opt for a more powerful database application for managing and analysing the results. From experience, it is advantageous to consider the long term needs for the database application at the outset and, if resources permit, to design the database accordingly. Also, if time permits, conducting an in-depth analysis of the results would allow for more effective transfer of knowledge to and exchange of knowledge with the general scientific community.

## REFERENCES TO ANNEX V


[V–1] HEALTH CANADA, Cross-Canada Survey of Radon Concentrations in Homes: Final Report, Health Canada, Ottawa (2012).

[V–2] LÉTOURNEAU, E.G., ZIELINSKI, J.M., KREWSKI, D., McGREGOR, R.G., Levels of radon gas in Winnipeg homes, Radiat. Prot. Dosim. **45** (1992) 531–534.

[V–3] LÉTOURNEAU, E.G., McGREGOR, R.G., WALKER, W.B., Design and interpretation of large surveys for indoor exposure to radon daughters, Radiat. Prot. Dosim. **7** (1984) 303–308.

[V–4] CHEN, J., BERGMAN, L., FALCOMER, R., WHYTE, J., Results of simultaneous radon and thoron measurements in 33 metropolitan areas of Canada, Radiat. Prot. Dosim. **163** (2015) 210–216.

[V–5] HEALTH CANADA, Radon Reduction Guide for Canadians, Health Canada, Ottawa (2013).

[V–6] FORD, K.L., HARVEY, B.J.A., WHYTE, J., CHEN, J., Predicting geographic variations of indoor radon potential across southwestern Ontario using geoscience data, Natural Resources Canada, Ottawa (2015).

## Annex VI

## NATIONAL RADON SURVEY IN ICELAND

The Icelandic Radiation Safety Authority (IRSA) conducted a nationwide indoor radon survey in 2012 and 2013. This was the first large scale study on radon indoors in Iceland. Two other smaller studies were done in 1982 and 2003.

In the 1982 study, measurements were made in 18 basements in four areas around Iceland, of which 10 were done in Reykjavik [VI–1]. The study in 2003 was a small research project at the University of Iceland [VI–2]. It focused on methods of measurement of radon indoors rather than the results of the measurements; 51 places in Reykjavik were measured.

Those earlier studies gave indications that radon levels indoors in Iceland were very low, as was assumed from what was known of radioactivity from natural sources in the Icelandic bedrock. Radon has also been widely studied in Iceland in connection with geothermal areas, and some measurements at hot springs have shown high concentrations of radon.

IRSA began work on conducting this study when the institute received an invitation from the European Joint Research Centre to contribute to the preparations for a European Atlas of Natural Radiation. The first milestone in that project was to prepare a map of radon levels indoors, using a grid with a resolution of 10 km × 10 km. One of the reasons for IRSA to conduct the survey was to confirm the low radon concentrations indoors that smaller studies had indicated.

### VI–1. NATIONAL DEMOGRAPHICS

Iceland has a surface area of 103 000 km$^2$. At the beginning of 2013, Iceland had 321 857 inhabitants and around 124 000 households. The population density was around 3.1 inhabitants per km$^2$. Most of the inhabitants of Iceland live near coastal areas and around 70% of the population live in or around the capital [VI–3].

### VI–2. SURVEY DESIGN

The detectors used were alpha track detectors, which are often used for a period of three months. IRSA wanted to try to use detectors for a longer time, both to have a lower detection limit and to obtain measurements over a longer period during the year.

The plastic used in the detectors deteriorates with time; however, the vendor stated that the changes in the plastic could be accounted for, so that they could be used for an entire year (with 15% uncertainty for 150 Bq/m$^3$). This meant that seasonal changes in radon concentrations did not have to be accounted for, and that saved time and money.

It was decided to advertise for volunteers to minimize the work for the survey and in the hope of achieving a higher retrieval rate. IRSA advertised on its web site and IRSA staff also asked family, friends and colleagues to participate. As radon has not been an issue in Iceland and the general knowledge of radon as a hazard was very limited, it is not likely that this approach to obtaining volunteers biased the results in any way.

Participants were sent one detector each and were given instructions describing where to place it (on a ground floor or in a basement and in rooms that they frequent). Some participants were given duplicate detectors for quality control purposes.

It was also decided to try to measure radon indoors at workplaces. Managers of kindergartens and swimming pools around Iceland were invited to participate. Kindergartens were selected because they are similar in the respect that most are in one floor buildings. Swimming pools were selected because they use large volumes of water, and a few of them also use geothermal water; however, most use groundwater heated with geothermal water in heat exchangers.

Some earlier measurements of air from hot springs in Iceland have yielded high radon concentrations. Workplaces around some of the largest geothermal plants in Iceland were therefore also invited to participate, and detectors were placed in three geothermal power plants.

At the end of the survey, participants were sent questionnaires about the placement of detectors together with prepaid envelopes for returning the detectors.

Low radon concentration indoors were expected, so there was some concern about whether the detectors might for some reason be put in places with high radon concentrations while being shipped from Iceland to Europe, where the results were to be read from the detectors. All the detectors were therefore vacuum packed in plastic before shipping.

To confirm that the vacuum packing worked, four detectors were placed in a storage room with a high activity radium source and therefore with a high radon concentration in the air. Two detectors that were not vacuum packed with plastic showed high radon concentrations (around 400 Bq/m$^3$); however, the other two detectors, which were vacuum packed in plastic, showed radon concentrations of around the detection limit of the detectors.

## VI–3. RESULTS AND ANALYSIS

For the survey, 500 alpha track detectors were used. A total of 285 people volunteered to measure radon indoors at their dwellings and 250 sent back the detectors. Regarding workplaces, 32 kindergartens and 30 swimming pools participated in the survey. Of the 32 kindergartens, 31 sent back their detectors. Responses from swimming pools were poorer as only 19 of the 30 sent back their detectors.

The results confirmed earlier studies, which found that radon concentrations in Iceland are very low. The arithmetic mean radon concentration was 13 Bq/m$^3$ and the median was 9 Bq/m$^3$. The distribution of the results is heavily biased towards the lower values, with a number of the results at or below the minimum detectable activity and 95% of the results below 40 Bq/m$^3$; the highest value recorded was 79 Bq/m$^3$ [VI–4].

No appreciable differences were found between the different regions of Iceland except that slightly higher values were observed in the north of the country. Measurements in kindergartens and swimming pools gave lower values than measurements in dwellings. The results from workplaces around geothermal power plants were very similar to other results but they were not grouped with the results from other workplaces.

These results, which match expectations given what is known about the Icelandic bedrock and from previous spot measurements, imply a mean dose to the population from exposure due to radon inhalation of 0.2 mSv/a. This value is almost certainly an overestimate, since only ground floors and basements were included in the study, while a large part of the population lives (and spends time indoors) on floors above ground floor, where the radon concentration is lower.

## VI–4. FOLLOW-UP ACTIONS

All participants were individually sent an email about the measurements made in their dwellings together with the arithmetic mean and median results. They were also informed about the limits in the European basic safety standards [VI–5].

The results were sent to the European Joint Research Centre and maps of the results were published on their web site.[1]

The IRSA published a report on the findings which clearly show that, in general, the Icelandic population does not need to be concerned about radon concentrations in their dwellings or workplaces [VI–4].

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[1] https://geoserver.jrc.ec.europa.eu/AtlasMap/map.aspx?layerId=3

## VI–5. POST-SURVEY CONSIDERATIONS

The results were satisfactory for the purpose of determining whether radon concentrations indoors in Iceland are below the reference level specified in the European basic safety standards [VI–5]. However, the data were not optimal for the purpose of accurately calculating the annual dose from radon, as most of the measurements were around or under the detection limit. Nonetheless, it was calculated that an earlier estimate of an annual dose of 0.2 mSv/a from radon exposure indoors in Iceland is not too low and is most likely an overestimation.

It would be interesting to try to find a correlation between different types of bedrock and radon concentration indoors, but because of the low measurements and the poor distribution of detectors, this might be difficult.

As most participants volunteered of their own accord, the retrieval rate was good and not much time was spent requesting that participants return their detectors. Some urban areas were missing from the results. IRSA could have been more active in advertising for or seeking volunteers in areas that were poorly represented in order to achieve a better coverage of Iceland and to obtain better statistics.

## REFERENCES TO ANNEX VI


[VI–1] ENNOW, K.R., MAGNÚSSON, S.M., Natural Radiation in Iceland and the Faroe Islands, National Institute of Radiation Protection, Copenhagen (1982).

[VI–2] JONSSON, G., Radon í andrúmslofti íbúða á Íslandi, University of Iceland, Reykjavík (2003).

[VI–3] STATISTICS OF ICELAND, Statistical Yearbook of Iceland 2013, Statistics of Iceland, Reykjavik (2013).

[VI–4] HALLDORSSON, O., Styrkur radons í húsum á Íslandi, Icelandic Radiation Safety Authority, Reykjavik (2014).

[VI–5] EUROPEAN COMMISSION, Council Directive 2013/59/EURATOM of 5 December 2013 Laying Down Basic Safety Standards for Protection Against the Dangers Arising from Exposure to Ionizing Radiation, and Repealing Directives 89/618/EURATOM, 90/641/EURATOM, 96/29/EURATOM, 97/43/EURATOM and 2003/122/EURATOM, EC, Brussels (2014).

## Annex VII

## NATIONAL RADON SURVEY IN ISLAMIC REPUBLIC OF IRAN

The Islamic Republic of Iran's strategy for radon measurements was initiated in 2015. A five year study is being conducted jointly by the Nuclear Science and Technology Research Institute, the Iran Nuclear Regulatory Authority, and the Ministry of Health and Medical Education. This annex reports on the methods and results of the pilot phase of the study conducted in Alborz province in 2016.

The aim of the full study is to obtain an estimate of the proportion of the Iranian population living in dwellings with radon gas levels above the WHO guideline of 300 Bq/m$^3$ (as well as >200 Bq/m$^3$ and >100 Bq/m$^3$), to identify previously unknown areas where radon gas exposure may constitute a health risk, and to build, over time, a map of indoor radon gas exposure levels across the country [VII–1].

The full study will also help to define potential radon prone areas, while providing the ability to search for possible correlations between radon levels and the characteristics of dwellings on the basis of data from the questionnaire.

### VII–1. NATIONAL DEMOGRAPHICS

The population of the Islamic Republic of Iran was 79.9 million as of the 2016 census [VII–2]. The levels of subdivision are 31 provinces, 429 counties, 1057 districts, 1245 cites and 2589 rural districts. As of 2016 there were 24.2 million households; how many of these were detached dwellings was unspecified [VII–2]. These numbers mean that on average, 3.3 persons live in each household.

### VII–2. SURVEY DESIGN

The Islamic Republic of Iran's national survey consists of six components: (a) establishing a National Radon Laboratory to support radon testing projects and to provide calibration services; (b) performing radon testing across the country; (c) creating a cooperation framework for dividing the duties of the survey among different institutes and authorities; (d) establishing a consulting agency for scientific and technical consulting; (e) conducting research projects on the health issues related to radon and on optimized methods for the Islamic Republic of Iran to reduce public exposure due to radon indoors; (f) and creating a programme to improve awareness on the part of homeowners and public health practitioners about health issues related to radon and methods of remediation.

The sampling strategy was designed on the basis of separating the territory of the country into 31 provincial units. To obtain an acceptable statistical power in every unit, the minimum number of samples was independently defined for each province. The province of Alborz, in which the pilot study is based, has a medium population size and a relatively small area.

The sampling strategy adapted for Alborz was stratified proportional random sampling which aimed to cover both rural and urban areas. Each rural district has a health centre that is responsible for all heath issues in the corresponding administrative division. Each health centre will therefore handle the distribution and collection of the samples in their areas under the supervision of the provincial health authorities. The principles that the strategy follows include:

— Only residential dwellings are included in the survey.
— All dwellings of a province are put in the same pool.
— Postcodes are used for random sampling.
— There is no limitation on the number of floors or the locations of the dwellings.
— High rise buildings are not numerous in the Islamic Republic of Iran and are not excluded from the study.

In the pilot phase, the study was designed to recruit about 1000 participants within one calendar year. After selection of the sample locations from postcodes, detectors were distributed by trained staff of the provincial Ministry of Health and Medical Education.

Oral explanations and brochures were first provided to residents to encourage them to participate in the project. Those who agreed to participate were given radon detector test kits and were asked to deploy two in their dwellings for a period of at least six months. They were trained in how to install the detectors in appropriate places in their dwellings and how to protect the detectors over the test period. Some of the guidelines for specifying the number of samples for each province are as follows:

— In order to be representative of the population, the number of radon measurements to be made in each province should be proportional, to the extent possible, to the number of dwellings.
— Imposing an upper limit (such as 2500 measurements) for provinces with a dense urbanized population (for example the province of Tehran, which is about 90% urban) seems reasonable.

— The statistical strength obtained for every province should meet a minimum acceptable level. To this end, the standard formula in Eq. (1) was adopted for calculating the minimum number of samples that are needed for every province. The assumptions were:
  - Radon concentration indoors follows a log-normal distribution; thus, if the sample number is greater, the accuracy of the results is greater.
  - Practically, it is desirable that not more than 5–15% of the dwellings in a country or province be above the national or provincial reference level.
  - In addition to the frequency distribution of the radon concentrations, the potentially high radon zones also have to be defined (this was not a focus of the pilot phase).

On the basis of these considerations, $p$ = 0.1 and $d$ = 0.02 ($d$ refers to the degree of precision) were set for defining the rate of dwellings above the reference level using Eq. (1).

— Because of the possible loss of samples during their distribution and return, or owing to physical damage and laboratory failures, an excess of 20% was added to the minimum sample number.

— In view of the number of rural districts in every province, extra samples were considered to ensure that each such unit receives a minimum of approximately five samples. In other words, low population areas may need to be oversampled (disproportionate random sampling) to avoid missing such areas owing to a sampling strategy that focuses on population only.

— A rate of 5% was considered for duplicate dosimeters (for quality assurance purposes).

— Some control detectors were to be used to verify whether 6 month and 12 month radon concentrations differ too greatly in a stratum. Just 2–3% of samples are enough control samples, and it is better for them to be installed in dwellings whose occupants show a high level of interest in cooperating with the survey (this was not done in the pilot phase).

$$n = \left[ \frac{z^2_{1-\frac{\alpha}{2}} \times p(1-p)}{d^2} \right] \tag{1}$$

for a confidence level of 95% $\left( z_{1-\frac{\alpha}{2}} = \frac{1}{96} \right)$, $n = 864$.

Such a sample size from each province will define the top 10% of dwellings with high radon readings with a 95% confidence level and plus or minus 2% error (which falls in the range of 8–12%).

From the 2011 census data that were used for the survey, the number of dwellings in Alborz was 712 664, with 8 counties, 16 cities and 22 rural districts. The approximate number of samples proposed was 1050.

### VII–2.1. Sampling technique

The survey is based on the following technical criteria:

- In order to obtain results representative of population exposure, two radon detectors are to be placed in separate inhabited rooms, such as the living room and one of the bedrooms. This allows information to be obtained on the variations in radon concentrations between rooms.
- If a dwelling has more than one floor, at least one room per floor is to be monitored in order to obtain information on the variations in radon concentrations between floors.
- If the lowest floor is a basement with a very low occupancy rate, the results of measurements of basement radon should not be used to estimate exposure of the population; this is because radon concentrations in basements can be quite different from concentrations in the rest of the dwelling.
- Distribution of detectors is carried out through direct delivery (face to face).
- Distributors of detectors are trained in how to explain the pilot study to the public.
- Frequently asked questions are anticipated and their answers are taught to distributors of detectors.
- The importance of the pilot study and its voluntary and charge free basis are broadcast provincially one to two week(s) before the distribution of detectors.
- Telephone numbers of dwellings where detectors are distributed are recorded in the questionnaire for the collection phase.
- In absence of the inhabitants of a dwelling, the detectors are delivered to a dwelling in the same neighbourhood or building.
- If an inhabitant does not assure the distributor of his or her presence for the next six months, inhabitants of a neighbouring unit will be recruited to substitute for him or her.
- Two pairs of detectors (the detectors of each pair attached to each other by tape) are delivered to the dwellings that are selected for installing the duplicates.

— A questionnaire containing the following information is filled out for every dwelling:
  - Postcode;
  - City or town;
  - Delivery date and collection date of the detectors;
  - Ownership or tenancy;
  - Contact number;
  - Floor number;
  - Identification of the detector;
  - Type of air-conditioning system;
  - Age of dwelling;
  - Type of contact at the base of the dwelling with the ground;
  - Type of structure (e.g. steel or concrete);
  - Floor surface material (e.g. stone, ceramic, concrete);
  - Family size;
  - Whether tobacco is smoked indoors.

— In addition to the explanations given, a single page guide that explains, in plain language, matters relating to radon and the correct use of the detectors is provided for each dwelling.

— Participants are contacted by telephone before the collection of detectors.

— Distribution of detectors through direct delivery is a time consuming approach. Dwellings that were delivered to earlier are collected from sooner.

The technical characteristics of the detectors and their packaging and subsequent processing are as follows:

— Lexan transparent polycarbonate films are used as detection strata.

— The films are put at the bottom of a diffusion chamber 86 mm tall with a volume 249 $cm^3$ that is covered by high efficiency particulate air filters to stop aerosols as well as radon progeny.

— The diffusion chambers are made of transparent plastic; this reassures the public that there is nothing suspicious inside the detectors.

— Diffusion chambers are labelled with the name of the pilot study, the distribution agency and the ID of the detector.

— Participants are trained to put both detectors 1–1.5 m above the floor, far from openings like windows and doors, not inside closets and out of reach of children.

### VII–2.2. Quality assurance programme

The quality assurance programme consists of the following elements:

— All procedures are specified and written (standard operating procedures).
— The minimum detectable concentration for the technique is specified and controlled whenever new batches of supplies such as Lexan film, chambers or air filters are used.
— The Iran Nuclear Regulatory Authority is equipped with a 'System for Test Atmospheres with Radon (STAR)' that took part in an international intercomparison exercise in 2011 and obtained good marks [VII–3].
— Performance tests and blind spikes: the Iran Nuclear Regulatory Authority acts as both the licensing body and the service laboratory for the plan, and thus relies only on the results that were obtained by its STAR in the international intercomparison in 2011.
— Calibration of detectors and continuous radon monitors is undertaken through the STAR and related standard procedures.
— Control of the background for passive (Lexan) detectors as well as the continuous monitors is done routinely.
— Detectors are sealed (inside radon resistant bags) from radon from the time at which they become ready to use until the bags are opened at dwellings.
— Detectors are sealed (inside radon resistant bags) from radon from the time at which they are collected from dwellings until the bags are opened at the laboratory for reading.
— Field background control measurements: 2–3% of detectors sealed from radon are kept unused as 'blank detectors' during every distribution; they have to undergo the same handling and storage conditions as other detectors except that they are not distributed among dwellings.
— Duplicate measurements are made (5% of samples are duplicated).
— The criteria for rejection of returned detectors are:
  - Any sign of unusual application of detectors (e.g. if the participant declares that the detector has been put inside a cabinet);
  - Any unusual condition of returned detectors (e.g. dirty or altered);
  - Ruptured filters;
  - Physical damage to detectors.

## VII–3. RESULTS AND ANALYSIS

The results from the pilot phase in Alborz indicate that 55% of the population are living in dwellings with radon levels above 100 Bq/m$^3$, while only 2% live in dwellings with radon levels above 300 Bq/m$^3$. Detectors were distributed to householders in 945 dwellings, of which the results in 822 cases were considered reliable.

### VII–3.1. Return rates of detectors

While the distribution of detectors was fully in accordance with the plan's time frame, the collection of samples satisfied the scheduled plan in 70.2% of cases and complied partially in 86.4% (70.2% + 16.2%) of cases.

### VII–3.2. Current situation of the project

Distribution of detectors in two other provinces started in December 2016 with the following quantities (owing to a lack of budget, the goal to distribute 1000 detectors has not been achieved):

— Khorasan Razavi: 850 detectors;
— Hormozgan: 750 detectors.

Collection of the samples was scheduled to commence in June 2017.

## VII–4. FOLLOW-UP ACTIONS

There had not been follow-up actions as of the time of writing because the study was currently under way.

## VII–5. POST-SURVEY CONSIDERATIONS

Some of the post-pilot study considerations are as follows:

— Preparation, coding and labelling of the detectors is a demanding task that, if not begun at the right time, could cause delay in the project.
— Duplicates are better delivered to participants who show a greater interest in cooperation with the project.
— The terminology used for introducing radon gas and the project to the public is crucial; it takes a great effort to find the best way to transfer the idea and the importance of the survey to the participants without alarming them.

— Contacting the participants by telephone to check the situation of the detectors, answer possible concerns and find out if there are broken detectors to replace can be a helpful approach to improve the conduct of the project.
— Training of staff who contact people is very important: just a simple half day or one day seminar at the beginning of the survey is not enough; a long time interval often occurs between the training and the distribution of detectors, and the staff need strong and continuous technical support.

## REFERENCES TO ANNEX VII


[VII–1] ATOMIC ENERGY ORGANIZATION OF IRAN, Iran National Plan for Survey of Radon Concentrations in Homes (Interim Report), AEOI, Teheran (2017).

[VII–2] IRAN DATA PORTAL, 2016 Census: Provincial Data, http://irandataportal.syr.edu/census/census-2016

[VII–3] JANIK, M., ISHIKAWA, T., OMORI, Y., KAVASHI, N., Technical Report on the Fourth International Intercomparison for Integrating Radon/Thoron Detectors with the NIRS Radon/Thoron Chambers, National Institute of Radiological Sciences, Chiba (2012).

## Annex VIII

## NATIONAL RADON SURVEY IN IRELAND

An extensive population weighted radon survey was carried out in Ireland between 1985 and 1989 [VIII–1]. The survey indicated that the likelihood of finding a dwelling with elevated radon concentrations indoors was greatest in the western part of the country, although dwellings with elevated radon concentrations were identified in most counties in Ireland.

Following this survey, the Radiological Protection Institute of Ireland (now the Environmental Protection Agency) undertook follow-up surveys in some of the areas identified as having dwellings with high radon concentrations. In general these follow-up surveys confirmed the results of the national radon survey and provided additional information on the distribution of radon in these areas [VIII–2].

In 1990, the Government adopted an annual average radon concentration of 200 Bq/m$^3$ as the national reference level above which corrective action to reduce the radon concentration in a dwelling ought to be considered.

To better quantify the extent of the population's exposure due to radon and to identify the areas of greatest risk, in 1992 the Radiological Protection Institute of Ireland initiated a geographically based national radon survey. The survey was carried out over a period of seven years and the results were published in 2002 [VIII–3].

### VIII–1. NATIONAL DEMOGRAPHICS

Ireland has a surface area of 70 280 km$^2$ and, at the time of the national radon survey, had a population of 3.56 million and approximately 1.3 million housing units. By 2015, the population had increased to 4.8 million, with a commensurate increase in the national housing stock [VIII–4].

Administratively, the country is divided into 26 counties, each of which is further divided into electoral divisions. Electoral divisions are the smallest legally defined administrative areas in Ireland for which population and health statistics are published. These administrative areas are irregular in both shape and size.

The survey used the Irish National Grid, which comprises 10 km × 10 km grid squares. There are 837 grid squares covering the surface area of the country.

At the time of the survey, most of the population lived in single family dwellings. In recent years, there has been an increase in the number of people living in apartments, particularly in urban areas, but as of 2014 this represented only about 5% of the population [VIII–5]. On a county level, the average population density in 2016 was 78 people per km$^2$, with a range from 20 people per km$^2$ in rural areas in the west of the country up to 1460 people per km$^2$ in the capital.

## VIII–2. SURVEY DESIGN

The national survey was based on the 10 km × 10 km national grid. This approach ensured that statistically valid sampling was possible, even in areas of low population.

The survey was carried out by the Radiological Protection Institute of Ireland in five separate phases between 1992 and 1999 [VIII–3]. The names and addresses of those people invited to participate were selected at random from the register of electors, and they were invited by letter to participate in the survey.

Statistical advice indicated that a minimum sample size of five dwellings per grid square was appropriate for this survey. To ensure this, a minimum of 50 householders from each grid square[1] were invited to participate in the survey. In 1995 this figure was increased to 70 householders from each grid square to improve the number of responses from each grid square. Local advertising was used to raise awareness of the survey and to maximize the response rates to letters of invitation to participate.

Each householder who volunteered to participate in the survey was provided with a map to indicate the exact location of the dwelling so that it could be assigned to the appropriate grid square. This was necessary because the postal address does not always adequately identify the exact location of the dwelling. The householder was also provided with a questionnaire, including questions about the physical features of the dwelling and the living habits of the occupants.

Two alpha track (CR-39) detectors were sent by post to all participants with instructions on where to place them — one in the living area and one in the main bedroom — for 12 months. The annual average radon concentration for each dwelling was calculated by averaging the results of the two measurements. At the end of the survey period the householder was sent a prepaid envelope in which to return the detectors.

[1] Names and addresses are available on the basis of electoral divisions and counties, but not on the basis of national grid squares. At the time of the survey, there was no national postcode system in place. The number of invitees per grid square was therefore only approximate.

## VIII–3. RESULTS AND ANALYSIS

Measurements were completed in a total of 12 649 dwellings. Afterwards, each result was considered valid if both of the detectors from the dwelling were returned and the grid square location of the dwelling was known. The final number of validated measurements was 11 319, with 993 dwellings exceeding the national reference level of 200 Bq/m$^3$. The arithmetic mean radon concentration was 89 Bq/m$^3$ and the maximum value was 1924 Bq/m$^3$.

Completed questionnaires were received from 89% of participants. Typical participation rates ranged from 17% to 36% for each county.

The distribution of radon concentrations was found to be approximately log-normal, at both the national level and the level of individual grid squares. A slight departure from log-normality was observed in the upper tail of the distribution, but the overall agreement was good.

It was found that the fit could be improved if 6 Bq/m$^3$ was subtracted from all radon concentrations; this value was taken to be the outdoor 'background' radon concentration. This figure was later confirmed by research to be the actual background radon level [VIII–6].

Statistical analysis, based on the geometric mean and geometric standard deviation, was carried out to determine the percentage of dwellings in any grid square predicted to exceed 200 Bq/m$^3$. This approach was applied to those grid squares for which there were five or more valid measurements.

In the 86 grid squares with fewer measurements, a smoothing procedure was carried out by using the available data for within the square and data for surrounding squares to calculate representative values for the geometric mean and geometric standard deviation.

On the basis of this analysis, five categories of 'radon related risk' were defined. These are grid squares in which it was predicted that <1%, 1–5%, 5–10%, 10–20% and >20% of dwellings respectively would have radon concentrations above the national reference levels of 200 Bq/m$^3$. Grid squares in which 10% or more of dwellings were predicted to have radon concentrations in excess of 200 Bq/m$^3$ were defined as high radon areas.

The survey predicted that 91 019 dwellings (at the time) throughout the country had radon concentrations that exceeded 200 Bq/m$^3$. Fully 28% of the grid squares were classified as high radon areas.

In total, 59 336 of the 91 019 dwellings in the country that were predicted to have high radon levels are located in high radon areas. This constitutes 65% of the total number of 'high radon homes' in the country and 21% of all dwellings within the high radon areas. Grid squares not classified as high radon areas include 78% of all dwellings throughout the country and encompass 72% of the surface area of the country.

By using an exposure to dose conversion of 1 mSv per 40 Bq/m$^3$, it is estimated that around 300 000 people receive annual radiation doses of above 5 mSv from exposure to radon in their dwellings.

## VIII–4. FOLLOW-UP ACTIONS

All householders were individually notified in writing of the results of their radon measurements and, where appropriate, recommendations were made regarding the necessity for corrective action.

A national map of radon predictions and similar county maps of radon predictions were published. These maps are used extensively to publicize the need for householders to undertake radon measurements, especially if they live in high radon areas.

The Radiological Protection Institute of Ireland established a commercial radon measurement service. Subsequently, several commercial companies established radon measurement services as well as services to reduce radon concentrations in existing dwellings and in other buildings.

Amended building regulations were introduced in December 1997, which require that measures be taken during construction to prevent the entry of radon into buildings from the underlying soil. The amended building regulations apply to buildings built on or after 1 July 1998. Technical guidance to support application of the new regulations was also published [VIII–7].

The new regulations require that the foundations in all new dwellings incorporate a potential means of extracting radon from the substructure (i.e. a standby radon sump). In addition, new dwellings in high radon areas are required to be fitted with a sealed membrane of low permeability.

In 1998 the Department of Education, with the support of the then Radiological Protection Institute of Ireland, began a radon survey of all primary schools and post-primary schools in the country. Between 1998 and 2002, measurements were completed in the ground floor classrooms and offices of 3444 schools in the country. Where necessary, corrective actions were carried out to reduce radon levels [VIII–8].

A number of policy documents were developed and contact was established with other national organizations and agencies, such as the Health Services Executive, the Sustainable Energy Authority of Ireland, the Health and Safety Authority and the Geological Survey of Ireland. Subsequently a National Radon Control Strategy was established.

## VIII–5. POST-SURVEY CONSIDERATIONS

According to the Radiological Protection Institute of Ireland, a number of things could have been done differently to avoid subsequent complications with the radon survey.

The grid on which the survey was carried out should have been designed to be directly comparable with the grid for data collected and collated by the Central Statistics Office. This would have allowed for greater comparability of statistics in relation to housing stock, demographics and other aspects.

In order to make the radon map simpler, three radon categories could have been chosen as opposed to five. Rather than using percentages, from the point of view of communications, designations of 'low', 'medium' and 'high' would have been preferable as this is more accessible to the general public.

The questionnaire used to collect data from the survey participants should have been tested with focus groups prior to use. This would have identified any questions that were unclear, as well as any additional information that should be collected.

It is important to consider follow-up surveys when planning a national radon survey: it could be very valuable to perform follow-up surveys on a reduced scale to track the impact of any actions to reduce radon levels. In Ireland's case, this will be undertaken every five years.

The subsamples would ideally consist of a relatively smaller number of dwellings compared with the initial national survey. The subsamples would give information on both the geographical distribution of radon levels and the population weighted distribution, the latter being the basis for estimating the health impact of any observed changes.

A methodology for undertaking a geographically based follow-up survey has been published [VIII–9]. This methodology classified the 10 km × 10 km grid squares by risk category and geographic region to identify grid squares that are statistically representative. Ultimately, 649 dwellings were tested by this method, resulting in a revised national indoor arithmetic mean radon concentration of 77 Bq/m$^3$.

The reduction in the mean radon concentration is considered to be attributable to the implementation of the amended building regulations from 1998. In addition, a population weighted methodology has been developed. The follow-up survey is in progress and results will be published in due course.

At the time of the survey, the Global Positioning System (GPS) did not exist and there was no national postcode system in place in Ireland. Today, identifying the exact locations of dwellings would be much easier. This would also allow the data to be compiled on the basis of electoral divisions, which might be of greater benefit to local planning authorities than maps based on the national grid.

The original map has now been redesigned to an interactive format that allows householders to search for their address to identify whether their dwelling is in a high radon area [VIII–10].

## REFERENCES TO ANNEX VIII


[VIII–1] McLAUGHLIN, J.P., WASIOLEK, P., Radon levels in Irish dwellings, Radiat. Prot. Dosim. **24** (1988) 383–386.

[VIII–2] MADDEN, J.S., et al., Radon in Dwellings in Selected Areas of Ireland, Rep. RPII-94/3, Radiological Protection Institute of Ireland, Dublin (1994).

[VIII–3] FENNELL, S.G., et al., Radon in Dwellings: The Irish National Radon Survey, Radiological Protection Institute of Ireland, Dublin (2002).

[VIII–4] WORLD BANK, Ireland Total Population 1960–2015, https://data.worldbank.org/indicator/SP.POP.TOTL?end=2015&locations=IE&start=1960

[VIII–5] EUROSTAT, Distribution of Population by Degree of Urbanisation, Dwelling Type and Income Group — EU-SILC Survey (2019), http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do

[VIII–6] GUNNING, G.A., POLLARD, D., FINCH, E.C., An outdoor radon survey and minimizing the uncertainties in low level measurements using CR-39 detectors, J. Radiol. Prot. **34** (2014) 457–467.

[VIII–7] DEPARTMENT OF THE ENVIRONMENT, Building Regulations 1997: Technical Guidance Document C — Site Preparation and Resistance to Moisture, Stationery Office, Dublin (1997).

[VIII–8] SYNNOTT, H., et al., Radon in Irish Primary and Post-Primary Schools: The Results of a National Survey, Rep. RPII-04/2, Radiological Protection Institute of Ireland, Dublin (2004).

[VIII–9] DOWDALL, A., et al., Update of Ireland's national average indoor radon concentration — Application of a new survey protocol, J. Environ. Radioact. **169–170** (2017) 1–8.

[VIII–10] ENVIRONMENTAL PROTECTION AGENCY, Radon Map (2019), http://www.epa.ie/radiation/radonmap/

## Annex IX

## NATIONAL RADON SURVEY IN ITALY

After local and sparse surveys that were carried out in the 1980s [IX–1], a national survey of about 5400 dwellings was carried out in Italy from 1989 to 1996. This allowed for a representative estimate of the distribution of the annual average radon concentration at a national level and a regional level to be determined [IX–2, IX–3].

This national survey was promoted and coordinated by the National Institute of Health and the former Italian National Agency for New Technologies, Energy and the Environment (currently the National Institute for Environmental Protection and Research), in collaboration with the 21 regional health authorities and the corresponding 21 regional reference laboratories for the control of environmental radioactivity (currently within the regional agencies for environmental protection).

Following this national survey, and on the basis of its results, more detailed surveys were carried out in several regions — mainly in schools [IX–4], but also in dwellings and workplaces [IX–5]. Most of them were focused on identifying radon prone areas [IX–6].

According to results from the Italian National Radon Archive, in total, more than 50 000 dwellings, schools and workplaces have been assessed (data updated to 2015) in radon surveys at the national, regional or subregional level carried out by national or regional public institutions involved in protection from radon exposure.

### IX–1. NATIONAL DEMOGRAPHICS

Italy is subdivided into 21 regions (formally 20 regions, but one of the regions is formed by two independent provinces), 14 cities and 96 provinces which in turn are subdivided into 7983 municipalities.

Italy has a surface area of 301 338 km$^2$, and the number of inhabitants was about 56 million persons in 1980 and 61 million in 2016. The number of dwellings was about 24 million, according to the last census carried out in 2011. A large portion of the population lives in the north of Italy (about 46%), 20% live in the centre and 34% in the south and the islands.

In Italy, 46 municipalities have more than 100 000 inhabitants, and two (Rome and Milan) have more than 1 million inhabitants. Overall, more than 35% of the population live in the territory of the cities, which includes the areas of 14 large municipalities together with their neighbouring towns.

## IX–2. SURVEY DESIGN

For the national survey carried out from 1989 to 1996, the sampling base was the list of families from the census of 1981. In order to be eligible, a dwelling had to be the intended main residence for a family for at least 12 months from the beginning of the survey.

In order to balance feasibility and precision of the estimations, a sample size of more than 5000 dwellings was chosen, which corresponds to a sampling proportion of about 1 in 4000 [IX–2], comparable with previous similar radon surveys carried out in other countries (e.g. the United Kingdom and the United States of America).

For each Italian region, simple random sampling was used for dwellings in large towns (i.e. those with more than 100 000 inhabitants in the census year 1981). For small towns (i.e. those with fewer than 100 000 inhabitants), cluster sampling was used, with random sampling of towns followed by random sampling of dwellings within the selected towns. In total, radon concentration measurements were carried out in 5631 dwellings distributed in 232 towns (50 large towns and 182 small towns).

The door to door approach was adopted for contacting families and distributing and retrieving radon detectors, in order to minimize non-response and refusal, which could lead to a biased sample.

Radon concentration measurements were performed using passive devices, each containing two alpha track detectors (LR-115 type II strippable), enclosed in a heat sealed polyethylene bag to block the entry of dust and radon decay products [IX–7], and also to minimize the entry of thoron [IX–8]. Track densities were read using a spark counting technique [IX–2].

In each dwelling, two devices were placed in one inhabited room, generally the bedroom, one at a time for two consecutive periods of about six months each in order to cover a full year of exposure. For each dwelling, the annual average radon concentration was estimated as the weighted average of the values for the two periods, in order to take into account any difference in the exposure times [IX–2]. For those dwellings (616) for which results for only one six month period were available, radon concentrations were seasonally corrected in order to have an unbiased estimate of the annual average concentration [IX–3].

## IX–3. RESULTS AND ANALYSIS

In Italy, the national annual average of the radon concentration, weighted by the population of each region, was assessed to be 70 Bq/m$^3$, with a geometric mean of 52 Bq/m$^3$ and a geometric standard deviation of 2.1 [IX–3]. The regional average ranged from about 25 Bq/m$^3$ to about 120 Bq/m$^3$.

Some regional radon distributions, especially for small regions where just a few small towns were sampled, had high uncertainties. This did not significantly affect the national distribution because of the small number of inhabitants compared with the entire population of Italy.

The estimated national average values of the fraction of dwellings with radon concentration above the reference levels of 150, 200 and 400 Bq/m$^3$ are 7.7%, 4.1% and 0.9%, respectively [IX–3].

The radon concentration values in the small town stratum are on average higher than those in the large town stratum (73 Bq/m$^3$ versus 62 Bq/m$^3$), because of a higher prevalence of low rise buildings and different soil characteristics.

Log-normal distribution obtained from the gross geometric mean and the geometric standard deviation (i.e. calculated from the data with no correction) led to a significant underestimation of the number of dwellings with radon levels higher than a reference level (i.e. equal to or higher than 200 Bq/m$^3$).

Better agreement between the high tails of the measured radon distribution and the corresponding ones estimated by the means of log-normal distribution was obtained by subtracting an outdoor radon value of 7 Bq/m$^3$ from each measured value. This subtraction led to an increased value of the geometric standard deviation, which became 2.5 (instead of 2.1) [IX–3].

The effect of soils as radon sources was clearly recognizable from the data, given the fact that a greater fraction of high values for radon concentrations were found in lower storeys. However, some high radon concentrations were also measured in dwellings on the first or the second floor, which suggested also a significant contribution from building materials. This was especially the case in some Italian regions where building materials with high exhalation of radon (such as volcanic tuff) were used.

Finally, it is worth noting that, thanks to the door to door approach, the percentage that did not respond was reasonably low (24% on average, 18% in small towns and 38% in large towns). In any case, checks on sample representativeness — performed by comparing several sample characteristics (e.g. year of construction and type of building) with those of the general populations — showed good agreement between the sample and the national situation [IX–2].

## IX–4. FOLLOW-UP ACTIONS

In 2013, all the regional average radon concentrations obtained in the national survey carried out in 1989–1996 were slightly updated, in order to evaluate the current health impact in terms of lung cancer deaths attributable to exposure due to radon [IX–9]. This update took into account: the non-linear response of radon detectors, updated population data from the last available census (2001), and the year to year variations of annual average radon concentrations estimated in an ad hoc study in Italy [IX–10].

The overall impact of this update was not high: it ranged from –1 to +2 Bq/m$^3$ for the regional averages and was about +1 Bq/m$^3$ at the national level. Following these corrections, it was estimated that the overall fraction of lung cancer deaths attributable to radon each year is about 10% (95% confidence interval: 3–18%), which corresponds to about 3300 lung cancer deaths annually (95% confidence interval: 1118–5882) [IX–9].

A more substantial update of radon distribution in Italian regions is in progress (as of 2017). This update takes into account: (a) the results of several regional surveys (involving a much higher number of dwellings compared with the national survey) and (b) the results of a proxy for a national survey that is representative of the population, which was carried out in 2010–2013 in all 110 Italian provinces and cities [IX–11].

### IX–4.1. Regional surveys in dwellings

Regional radon surveys were carried out in 16 Italian regions, in which more than 27 000 dwellings were included, according to the Italian National Radon Archive. Most of these surveys were carried out in dwellings mainly located on the ground floor or the first floor. The dwellings sampled were therefore not fully representative of all dwellings, generally resulting in an overestimation of the actual radon distribution.

A study is in progress that takes into account the housing stock in the updated census and how radon concentrations vary as a function of the floor level. This will aid in correcting the results of the regional survey, and the regional and national radon distributions will subsequently be updated.

### IX–4.2. Proxy for a national survey that is representative of the population

The sampling base for this survey was different from the Italian population as a whole — it involved a sample of dwellings of the employees of a national company — and therefore it needs a careful representativeness check, and an ad hoc correction procedure in case this check fails for some strata [IX–11]. After these corrections, data and results from this survey will significantly increase the information content of the radon distribution for Italy, since data will be available for all the Italian provinces and cities.

## IX–5. POST-SURVEY CONSIDERATIONS

In the framework of the first national survey, all the Italian regions established regional laboratories and professional expertise in the measurement techniques for radon concentrations. Since the 1990s, therefore, Italy has developed a network of laboratories able to perform measurements of radon concentrations. This has made it relatively convenient to perform further regional or subregional radon surveys, which were mainly focused on identifying radon prone areas.

Regarding the first national survey, the main positive results are the following:

— The survey was effective in increasing the radon expertise of the personnel of the 21 regional laboratories.
— There was a good involvement of (and collaboration among) national and regional authorities, which was useful for several actions relating to the survey, including informing the public. These positive considerations are reflected in the costs and the time required to conduct such surveys.

Some specific elements could be improved upon:

— Two rooms could be monitored per dwelling instead of only one.
— Duplicate detectors (for estimating the in-field uncertainty) could be used in only about 10% of dwellings rather than in all of them. In this way, the number of detectors needed would be reduced without any loss of data on the in-field uncertainty.
— To reduce the cost per dwelling, a single detector could be exposed for a period of one year, instead of using two detectors for consecutive periods of six months each; in addition, this would eliminate the need to correct for seasonal variations.
— Finally, with the door to door approach that was adopted for contacting inhabitants, distributing and retrieving detectors, and completing the questionnaire, the samples for a total of 232 towns (of the nearly 8000 for Italy) were put into clusters. This was done for reasons of feasibility and cost, so that an approach based on mail, telephone and email could be adopted (either as an alternative or in addition), which would be less expensive and more feasible for selecting samples more spread out over the territory. These improvements were subsequently applied in the second national survey [IX–11].

## REFERENCES TO ANNEX IX


[IX–1] CAMPOS VENUTI, G., et al., Indoor exposure in a region of central Italy, Radiat. Prot. Dosim. **7** (1984) 271–274.

[IX–2] BOCHICCHIO, F., et al., Results of the representative Italian national survey on radon indoors, Health Phys. **71** (1996) 741–748.

[IX–3] BOCHICCHIO, F., et al., Annual average and seasonal variations of residential radon concentration for all the Italian regions, Radiat. Meas. **40** (2005) 686–694.

[IX–4] GAIDOLFI, L., et al., Radon measurements in kindergartens and schools of six Italian regions, Radiat. Prot. Dosim. **78** (1998) 73–76.

[IX–5] BUCCI, S., et al., Radon in workplaces: First results of an extensive survey and comparison with radon in homes, Radiat. Prot. Dosim. **145** (2011) 202–205.

[IX–6] BOCHICCHIO, F., et al., "Areas with high radon levels in Italy", Proc. Workshop on Radon in the Living Environment Athens, 1999, Sci. Total Environ. **272** (2000).

[IX–7] AZIMI-GARAKANI, D., et al., Radon gas sampler for indoor and soil measurements and its applications, Radiat. Prot. Dosim. **24** (1988) 269–272.

[IX–8] BOCHICCHIO, F., et al., Sensitivity to thoron of an SSNTD-based passive radon measuring device: Experimental evaluation and implications for radon concentration measurements and risk assessment, Radiat. Meas. **44** (2009) 1024–1027.

[IX–9] BOCHICCHIO, F., et al., Quantitative evaluation of the lung cancer deaths attributable to residential radon: A simple method and results for all the 21 Italian regions, Radiat. Meas. **50** (2013) 121–126.

[IX–10] BOCHICCHIO, F., et al., Results of the first 5 years of a study on year-to-year variations of radon concentration in Italian dwellings, Radiat. Meas. **44** (2009) 1064–1068.

[IX–11] ANTIGNANI, S., et al., An affordable proxy of representative national survey on radon concentration in dwellings: Design, organisation and preliminary evaluation of representativeness, Radiat. Meas. **50** (2013) 136–140.

## Annex X

## NATIONAL RADON SURVEY IN MONTENEGRO

Recognition of radon as a potential health risk in Montenegro is low. Until recently there were only a dozen specialists, from various fields, who were somewhat familiar with risks relating to radon.

In 1998, Montenegro adopted an annual average radon activity concentration of 400 Bq/m$^3$ as the national reference level for existing dwellings and 200 Bq/m$^3$ for dwellings to be built in the future [X–1]. This decision was based on the recommendations of the International Commission on Radiological Protection, but without knowledge of the present radon situation in the country.

Preparation of the first nationwide systematic indoor radon survey commenced in 2000 and radon measurements were performed in dwellings in half of the country's territory in 2002–2003 [X–1]. The survey in the rest of the country was not completed in that time period owing to lack of funds.

The survey was completed in 2017 as a result of the conduct of the national project on radon mapping and upgrading the national system for radon protection, which was started in 2014. The national project on assessing and reducing radon in schools and kindergartens was begun in 2016 and continued until the end of 2018. Both projects are funded by the IAEA and the Government of Montenegro.

### X–1. NATIONAL DEMOGRAPHICS

Montenegro has a surface area of 13 812 km$^2$. In 2011, the national census calculated a population of 620 029, which remains more or less stable. The average population density is 45 persons per km$^2$, with a range (average per municipality) of 4 to 305 persons per km$^2$. At the time of the census there were 125 000 permanently inhabited dwellings with an average of 3.1 persons per dwelling [X–2].

Montenegro has 23 municipalities, each named after its largest town. Unofficially, the country is also divided into three regions, called the coastal region (six municipalities), the central region (four municipalities) and the northern region (13 municipalities). The population distribution between the three regions is 24%, 47% and 29% respectively. Approximately two thirds of the population live in urban areas and one third in rural areas [X–2].

## X–2. SURVEY DESIGN

A combination of a geographically based survey and a population weighted survey was chosen for the radon survey in Montenegro. The first type of survey is based on a national grid of 5 km × 5 km squares, with 552 squares in it. Of these, 64 squares have no dwellings with permanent inhabitants [X–3].

The second type of survey is based on both the national grid and the local grids. The local grids are established in the main towns and have a finer mesh of 0.5 km × 0.5 km. In each of the squares from both grids, one dwelling on the ground floor or the first floor was selected for the radon survey [X–4].

Dwellings for the radon survey were not selected completely randomly. This was not possible because the Personal Data Protection Law does not allow use of the register of electors, the addresses of telephone users or electricity users, or similar lists for a purpose such as the radon survey. Advice from geologists and building experts was therefore obtained to identify what could be regarded as a characteristic dwelling in each grid square, and such a dwelling was then selected directly in the field.

The national survey was carried out in two phases. The coastal and central regions were surveyed in 2002–2003, and in 2014–2015 the survey was completed with radon measurements in the northern region and in areas where detectors were lost in 2002–2003.

Track etch (CR-39) detectors were used for both phases of the survey. In the first phase, ‘basic’ radon detectors were purchased from Italy and ‘control’ detectors (numbering about 10% of the total) were provided by the Jožef Stefan Institute, Slovenia, where both types of detector were calibrated and analysed.

In the second phase, basic detectors and control detectors were also purchased from abroad, from two independent accredited radon measurement laboratories. Detectors from two different origins were used to double check the accuracy of the results. Following exposure, the detectors were returned to the laboratories for analysis.

The measurement protocol in both surveys involved two separate six month measurement periods in each of the selected dwellings, covering the summer (April to September) and winter (October to March) periods. One measurement was made in either the living area or the bedroom: participants were permitted to choose their preferred location.

In order to check the consistency and accuracy of measurements, in approximately 10% of dwellings two basic detectors were placed side by side, and in another 10% of dwellings a basic detector was paired with a control one. Generally the results from the paired detectors showed good agreement, within 10% in the first phase and within 5% in the second phase of the survey.

A door to door approach was used in both phases of the survey. In the first phase, members of the expert team for the radon survey went from the capital city of Podgorica to each of the selected locations to speak to householders, to place detectors and to complete the questionnaire on physical features of dwellings and living habits of their occupants.

In the second phase, 25 members of 11 local teams were selected and trained for doing such field work. The second solution has proved to be more effective because owners of dwellings had more confidence in the locals known to them than in people from the capital.

The percentage of detectors that went missing in the first phase was 20% and in the second phase only 2%.

## X–3. RESULTS AND ANALYSIS

In the first phase of the national radon survey, measurements were completed in at least one of the six month periods in 434 dwellings [X–1], and measurements in the second phase were completed in at least one of the six month periods in 661 dwellings.

Correlation coefficients between radon concentrations in dwellings in summer and in winter are calculated for each of the three distinct climate zones in Montenegro and then applied to the missing data for seasonal six month measurements. In this way, only six inhabited squares from the national 10 km × 10 km grid remained with no results for average annual indoor radon concentration.

Valid results for radon concentrations were obtained for 1095 dwellings in Montenegro.

The national average radon activity concentration in Montenegro dwellings was 110 Bq/m$^3$ and the median was 52 Bq/m$^3$. The maximum concentration was 2321 Bq/m$^3$. Radon concentrations above the national reference level of 400 Bq/m$^3$ were found in 4.6% of all dwellings sampled, and radon concentrations above the level of 300 Bq/m$^3$, which is recommended by European Commission Council Directive 2013/59/EURATOM as the highest national reference level [X–5], were measured in 7.9% of all dwellings sampled.

The arithmetic mean radon concentration in urban dwellings was 86 Bq/m$^3$, and in rural dwellings it was 144 Bq/m$^3$. In single family detached houses, the average radon concentration was 117 Bq/m$^3$, while in apartments it was 48 Bq/m$^3$.

On the basis of the measurements made during the national survey, average values of radon activity concentration for each municipality were calculated. These ranged from 40 Bq/m$^3$ to 201 Bq/m$^3$. The average radon concentrations were also calculated for each of 131 squares of the 10 km × 10 km grid; these were in the range of 30 Bq/m$^3$ to 732 Bq/m$^3$.

A statistical method, based on the geometric mean and geometric standard deviation of transformed experimental data sets, was applied to estimate the percentage of dwellings above a certain radon level in the country and in each of the municipalities. It was found that the percentage of dwellings with a radon level above 300 Bq/m$^3$ is the highest in six municipalities, where it is between 10% and 18%.

The same method was applied to each of 10 km × 10 km grid squares in Montenegro, but it produced results with high uncertainties owing to the small number of measurements for most of the grid squares.

## X–4. FOLLOW-UP ACTIONS

Confidential letters were sent individually to all householders in the 1095 dwellings sampled, with the results of the radon measurements made in their dwellings, their interpretation and recommendations about the necessity for remediation.

Three types of radon maps of Montenegro were created. They present average radon concentrations indoors in the squares of a 10 km × 10 km national grid, average radon concentrations in the municipalities, and the percentage of dwellings with radon concentrations above 300 Bq/m$^3$ in the municipalities.

The local expert team that conducted the national indoor radon survey prepared a document as the base for developing the Strategy and Action Plan for protection against radon in Montenegro, which was submitted to the Government. Among the many other considerations in this document, the expert team suggested the following:

- Adoption of 300 Bq/m$^3$ as the reference level for existing buildings and 150 Bq/m$^3$ for new ones;
- An action level of 1000 Bq/m$^3$, above which remediation ought to be strongly recommended to the householders and financially supported by the state budget;
- A definition of radon priority areas as the entire territory of a municipality in which more than 10% of dwellings have radon concentrations above the national reference level.

By the end of 2017, it is envisioned that the Government of Montenegro will adopt the Strategy and Action Plan for protection against radon. The Government will also consider the proposal to establish a new Law on Spatial Planning and

Construction, which will be likely to take into account the protection against radon in the planning and construction of buildings.

In 2015, a training programme on radon diagnostics and remediation to reduce radon concentrations in existing buildings was initiated. In 2016, two primary schools with high radon concentrations were successfully remediated.

In 2016, a national survey of radon in schools commenced. Measurements were undertaken in every school and kindergarten in Montenegro, in every classroom and office on the ground floor and in some on the first floor, throughout the school year from September 2016 to June 2017.

The Centre for Ecotoxicological Research is now equipped with electret and nuclear track detector systems. After appropriate accreditation, the Centre will be able to perform numerous medium term and long term radon measurements simultaneously.

Establishment of the first radon calibration laboratory in the Bureau of Metrology in Podgorica is under way. All necessary equipment has been purchased and is to be installed in 2017. This laboratory is expected to contribute significantly to the quality of radon measurements not only in Montenegro but also in neighbouring countries.

Much work on communication on radon related risks has been done in Montenegro in the past three years. Public lectures were given in every municipality, thousands of flyers on radon in dwellings and radon in schools were distributed, interviews were given to the electronic media and to the print media, and several press conferences were held.

In spite of this, a survey of public opinion on radon, conducted in November 2016 from a sample of 1014 adult citizens all over the country, showed that only 15% of them had some knowledge about radon and that 52% of citizens would like to have more information about the radon concentration in their dwellings.

## X–5. POST-SURVEY CONSIDERATIONS

The first national indoor radon survey provided results that are a good basis for a more comprehensive national policy concerning protection against radon. This national policy will be effected through the National Strategy and new related legislation, resulting especially in preventive measures during the planning and construction of new buildings.

New equipment in the Centre for Ecotoxicological Research will enable a continuously growing number of radon measurements to be made in dwellings, workplaces and public buildings, with a special emphasis on municipalities with relatively high average radon concentrations.

Efforts to increase public awareness of radon are necessary, and well organized training programmes are necessary in order to achieve an urgent increase in the number of professionals and companies available for radon measurements and for remediation.

## REFERENCES TO ANNEX X


[X–1] VUKOTIC, P., ANTOVIC, N., ZEKIC, R., SVRKOTA, R., Indoor radon concentrations in the coastal and central regions of Montenegro, Proc. 12th IRPA Congress, Buenos Aires (2012).

[X–2] STATISTICAL OFFICE OF MONTENEGRO, 2011 Statistical Yearbook, MONSTAT, Podgorica (2011).

[X–3] ANTOVIC, N., VUKOTIC, P., ZEKIC, R., SVRKOTA, R., ILIC, R., Indoor Radon Concentrations in Urban Settlements on the Montenegrin Coast, Rad. Meas. **42/9** (2007) 1573–1579.

[X–4] VUKOTIC, P., ANTOVIC, N., ZEKIC, R., SVRKOTA, R., ILIC, R., Indoor Radon Concentrations in Four Municipalities of the Central Part of Montenegro, J. Res. Phys. **32/1** (2007) 1–15.

[X–5] EUROPEAN COMMISSION, Council Directive 2013/59/EURATOM of 5 December 2013 Laying Down Basic Safety Standards for Protection Against the Dangers Arising from Exposure to Ionizing Radiation, and Repealing Directives 89/618/EURATOM, 90/641/EURATOM, 96/29/EURATOM, 97/43/EURATOM and 2003/122/EURATOM, EC, Brussels (2014).

## Annex XI

## NATIONAL RADON SURVEY IN NETHERLANDS

The first nationwide radon survey in the Netherlands was conducted in the early 1980s [XI–1]. The next radon survey was limited to dwellings built after the previous survey [XI–2]. These surveys showed that radon concentrations in Dutch dwellings are low in general, compared with radon concentrations in dwellings in many other countries in Europe and elsewhere.

For this reason, the Netherlands did not adopt a specific reference level for radon in dwellings at that time. Instead, an agreement was signed with the construction industry to maintain the favourable radiation conditions in Dutch dwellings, establishing a 'standstill'.

Unexpectedly, data from a third radon survey showed a large discrepancy from previous results: the newly obtained radon data [XI–3] were lower by a factor of almost two on average compared with the results from the first two surveys. Subsequent research determined that: (a) radon detectors used in the early days were also susceptible to thoron; and (b) there were indications that concentrations of $^{220}$Rn progeny in Dutch dwellings were higher than previously anticipated [XI–4, XI–5].

It was therefore decided to conduct a new nationwide survey to measure both radon progeny and thoron progeny in a representative group of approximately 2500 Dutch dwellings built since 1930. This survey took place in the period 2013–2014. The results, which were published in 2015 and later [XI–4, XI–6 to XI–8], were used to support the establishment of a reference level for radon in dwellings, as required by the European Commission Council Directive 2013/59/EURATOM [XI–9].

To date, a national database for indoor radon is available only for dwellings, but a large survey in workplaces and public buildings (including the measurement of thoron progeny and gamma radiation) is currently in progress.

### XI–1. NATIONAL DEMOGRAPHICS

The Netherlands has a surface area of 41 543 km$^2$ and has some 17 million inhabitants at present. The Dutch population is expected to stabilize over the coming decades at a maximum of approximately 18 million.

At the time of the survey, the Dutch housing stock comprised almost 7.3 million dwellings in total. About one third of these are multistorey dwellings, which are found more often in the western part of the Netherlands.

Approximately 15% of the current housing stock was built before 1930. Pre-1930 dwellings form a very heterogeneous group, ranging from grand sixteenth century canal houses in Amsterdam to poorly built dwellings from the beginning of the twentieth century.

These dwellings are seldom in an original state, and reliable information about the period of construction, the characteristics of the buildings and any reconstruction work is often lacking. It is therefore difficult to draw a representative sample of this group, to relate radon data for this group to ‘typical characteristics’ of these dwellings and to formulate appropriate corrective measures, if necessary. Moreover, the relative number of dwellings in this group is declining. It was therefore decided to limit the 2013–2014 radon (and thoron progeny) survey to dwellings built after 1929 [XI–4].

## XI–2. SURVEY DESIGN

At first, a random selection of approximately 10 000 dwellings was made, representing the group of Dutch dwellings built in the 1930–2012 period. The residents of some 2900 dwellings responded positively to a request to participate in this survey. In 2013, these residents received two passive detectors: one radon detector and one thoron progeny detector.[1] The radon detector was a CR-39 based alpha track detector [XI–10].

All participants were asked to complete a questionnaire with characteristics of their dwelling (type of ventilation system, the room where the detectors were mounted) and their habits (for instance, whether they regularly smoke in the dwelling or not).

After a period of at least one year, both detectors were sent back to the Dutch National Institute for Public Health and the Environment. The survey yielded 2562 valid records of annual average radon concentrations (and 2461 for thoron progeny). Completed questionnaires were available for almost 95% of these records.

## XI–3. RESULTS AND ANALYSIS

The annual average activity concentration of radon in dwellings in the Netherlands was 15.6 ± 0.3 Bq/m$^3$. The 50th and 95th percentiles were found to be 12.2 Bq/m$^3$ and 38.0 Bq/m$^3$, respectively. Radon concentrations exceeded

[1] The thoron progeny detector applies four CR-39 chips covered with an aluminium–vaporized Mylar film, detecting exclusively the 8.78 MeV alpha particles emitted by $^{212}$Po.

100 Bq/m$^3$ in 0.4% of the dwellings. These values are at the lower end of those reported for many other European countries. Radon concentrations showed correlations with type of dwelling, year of construction, ventilation system, location (soil type) and smoking behaviour of inhabitants [XI–4].

Based on the results of this survey, of the existing 6.2 million dwellings in the Netherlands built since 1930, approximately 24 000 are believed to exceed the 100 Bq/m$^3$ level. Around 80% of these are located in the relatively small group of naturally ventilated single family houses in two designated areas: South Limburg, where there are approximately 13 000 homes, and the Meuse–Rhine–Waal river delta, with approximately 6000 homes. Soil characteristics in these regions (loam in South Limburg and river clay in the Meuse–Rhine–Waal river delta) result in a higher rate of radon entry into buildings in comparison with elsewhere in the Netherlands [XI–4].

## XI–4. FOLLOW-UP ACTIONS

All householders were individually notified in writing of the results of the measurements made in their dwellings, and also received a leaflet and a report with the results of the survey. Where appropriate, recommendations were made to increase the ventilation in their dwellings. Supplementary information is available on the web site of the Dutch National Institute for Public Health and the Environment[2] [XI–7].

## XI–5. POST-SURVEY CONSIDERATIONS

Under European Commission Council Directive 2013/59/EURATOM [XI–9], all Member States of the European Union are required to establish a national action plan addressing long term risks from exposure due to radon in dwellings. The main requirements for this plan are: to select a national reference level for the annual average activity concentration of radon in dwellings, to promote actions to identify dwellings with radon concentrations that might exceed the national reference level, and to encourage appropriate corrective measures to reduce the radon concentrations in these dwellings.

The Netherlands intends to adopt a reference level of 100 Bq/m$^3$, in line with recommendations by the World Health Organization and the International Commission on Radiological Protection. The other requirements will be

[2] https://www.rivm.nl/binnenmilieu/radon

elaborated in the Dutch National Radon Action Plan, which is intended to be adopted in 2018.

Radon concentrations above 200 Bq/m$^3$ are rare in the Netherlands. So, simple and inexpensive measures are expected to be sufficient to reduce elevated radon concentrations to values well below the intended national reference level of 100 Bq/m$^3$ [XI–6, XI–4].

## REFERENCES TO ANNEX XI

[XI–1] PUT, L., VELDHUIZEN, A., DE MEIJER, R., Radonconcentraties in Nederland, Verslag van SAWORA: Project A2, Rep. KVI-111i, Rijksuniversiteit Groningen, Groningen (1985).

[XI–2] STOOP, P., GLASTRA, P., HIEMSTRA, Y., DE VRIES, L., LEMBRECHTS, J., Results of the Second Dutch National Survey on Radon in Dwellings, Rep. 610058006, Dutch National Institute for Public Health and the Environment, Bilthoven (1998).

[XI–3] BADER, S., DEKKERS, S., BLAAUBOER, R., Stralingsbelasting in Nederlandse nieuwbouwwoningen: Eindrapport ventilatie- en radononderzoek, Rep. 610790009, Dutch National Institute for Public Health and the Environment, Bilthoven (2010).

[XI–4] SMETSERS, R., BLAAUBOER, R., DEKKERS, F., Ingredients for a Dutch radon action plan, based on a national survey in more than 2500 dwellings, J. Environ. Radioact. **165** (2016) 93–102.

[XI–5] BLAAUBOER, R., Meetmethoden thoron in survey, VERA-onderzoek, Rep. 610890001, Dutch National Institute for Public Health and the Environment, Bilthoven (2012).

[XI–6] SMETSERS, R., Woningen in Nederland met mogelijk hogere radonconcentraties: Onderzoek voor de implementatie van richtlijn 2013/59/EURATOM, Rep. 2017-0032, Dutch National Institute for Public Health and the Environment, Bilthoven (2017).

[XI–7] SMETSERS, R., BLAAUBOER, R., DEKKERS, F., VAN DER SCHAAF, M., SLAPER, H., Radon en thoron in Nederlandse woningen vanaf 1930: Resultaten RIVM-meetcampagne 2013–2014, Rep. 2015-0087, Dutch National Institute for Public Health and the Environment, Bilthoven (2015).

[XI–8] SMETSERS, R., BLAAUBOER, R., SLAPER, H., DEKKERS, F., "Radon and thoron in Dutch dwellings", Proc. Third East-European Radon Symp. Sofia, 2017, J. Environ. Radioactivity (in press).

[XI–9] EUROPEAN COMMISSION, Council Directive 2013/59/EURATOM of 5 December 2013 Laying Down Basic Safety Standards for Protection Against the Dangers Arising from Exposure to Ionizing Radiation, and Repealing Directives 89/618/EURATOM, 90/641/EURATOM, 96/29/EURATOM, 97/43/EURATOM and 2003/122/EURATOM, EC, Brussels (2014).

[XI–10] DURRANI, S.A, ILIC, R., Radon Measurements by Etched Track Detectors, World Scientific Publishing, Singapore (1997).

# Annex XII

## NATIONAL RADON SURVEY IN UNITED STATES OF AMERICA

In October 1986, Congress directed the Environmental Protection Agency (EPA) to “assess the radon levels in the nation’s homes as part of a larger research effort to address a growing concern over how significant the health threat was from indoor radon” [XII–1]. At the time, a study had been carried out by Lawrence Berkeley National Laboratory [XII–2] and, on the basis of those results, the EPA estimated in 1986 that between 5000 and 20 000 people could be dying each year in the United States of America (USA) owing to residential radon exposure.

Separately, elevated radon concentrations had been found in dwellings in certain areas of the USA, such as the Reading Prong area of New York, New Jersey and Pennsylvania, and in homes built on uranium-bearing mining wastes in parts of Colorado and Florida. Based on an analysis of radon testing data, the EPA subsequently came to the view that many more homes than originally estimated could have elevated radon concentrations.

The EPA conducted a population weighted national radon survey, referred to as the National Residential Radon Survey (NRRS), in the USA with the aim of calculating the distribution of radon concentrations in dwellings. The results of the survey were published in 1992 [XII–1]. Planning and pretesting of the survey took place between 1986 and early 1989; data collection took place from mid-1989 to late 1990, and editing and statistical analysis took place from 1990 to 1992.

### XII–1. NATIONAL DEMOGRAPHICS

In 1990, the USA had a population of 248.7 million with 91.9 million occupied dwellings, giving an average of 2.7 persons per dwelling. Of the 91.9 million occupied dwellings, 55.5 million were detached [XII–3]. Administratively, the country is divided into 50 states. The states are further divided into counties, which may then be divided into townships.

The analysis was performed on a countywide basis; no grid system was used.

## XII–2. SURVEY DESIGN[1]

The survey aimed to measure radon levels in housing units and collect completed questionnaires from the permanent occupants of these housing units. To be selected, participants had to be residents whose dwellings were their primary residence, who had no plans to move within the next 12 months and who would be occupying their dwellings for at least nine months during the measurement period. The reason for this was to exclude vacation homes, which are occupied infrequently. Residents of dwellings that were located on military installations or in thinly populated areas of Alaska were excluded from the survey.

The survey included single family detached dwellings, multi-unit structures (apartments) and mobile homes. It did not cover group quarters such as college dormitories and prisons.

The EPA partitioned the country into 22 strata for sampling purposes in order to ensure ample coverage for areas expected to have differing levels of radon. A multistage sampling process was used to select the sample: 125 primary sampling units, areas the size of one or more counties, were selected nationwide.

Within each primary sampling unit, a random sample of secondary sampling units, which were small land areas such as census blocks, were selected. Housing units within secondary sampling units were then randomly selected to be part of the sample.

The information about the participants' dwellings, movements within their dwellings, tobacco smoking habits and steps that they may have taken to measure and to reduce radon levels was collected through personal interviews. The EPA assisted homeowners in placing alpha track detectors in their dwellings: one for each floor, and two placed in appropriate locations if the dwelling had only one floor. During the year long measurement period the EPA monitored the participation of the residents involved and replaced lost or damaged detectors.

Many steps were taken during the survey to ensure that meaningful information and measurement data were collected and were entered properly into a data system for purposes of statistical analysis. The questionnaire and the procedures for the placement of detectors were pretested with 60 respondents, and the final questionnaire and detailed field procedures were designed on the basis of this experience.

The EPA encouraged public participation to ensure a high response rate, monitored participation by residents every quarter and addressed detector issues as they arose. Detectors and their retrieval forms were carefully checked and accounted for, and the EPA ensured that the radon levels from the alpha track detectors were measured accurately at the laboratory.

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[1] The sections on survey design and results are from Ref. [XII–1].

One important point to note is that the EPA met the survey's objectives for precision. It was determined through the audit of the data for quality that the measurements collected could be reliably used for estimating radon levels, and also that the response rate was sufficient to meet the objectives for precision that the EPA had established.

The number of dwellings from which the EPA aimed to acquire measurements was 5000. The initial sample of dwellings drawn for the survey was 11 423, to ensure that reliable measurements would be obtained. There were 7118 respondents who participated and measurement data were obtained from 5694 dwellings by the end of the survey.

Questionnaire responses were also reviewed for quality purposes, as some respondents were unable to provide accurate responses to questions about how much time members of their households spent on different floors and how much time they spent in the dwelling in general. The EPA has therefore used the data on housing characteristics cautiously in its analysis.

## XII–3. RESULTS AND ANALYSIS

The NRRS obtained three types of result. First, national and regional estimates of annual average radon concentrations were derived for different components of the housing stock. Second, statistics on housing characteristics, living habits and the percentage of households that tested for radon levels and that reduced their levels of exposure were assembled. Lastly, housing and household characteristics that appear to affect radon levels in dwellings most significantly were identified.

### XII–3.1. National and regional radon concentrations in dwellings

The results of the NRSS were used to estimate annual average radon levels for dwellings throughout the USA and dwellings within the ten EPA regions, and for different components of the housing stock. There were three approaches considered to estimate annual averages for dwellings covered by the survey: lowest lived-in level (storey), average concentration over all lived-in stories, and average concentration over all lived-in storeys weighted for residents' occupancy rates for different levels in the dwelling.

The third most accurately reflects the ideal way to assess annual averages in a dwelling because an individual's risk of getting lung cancer is directly proportional to his or her integrated exposure on all levels. However, as mentioned previously, the EPA believes that many respondents were unable to provide answers to the survey questions that could form the basis for meaningful results.

The EPA therefore used the average concentration over all lived-in housing levels to estimate the annual average radon level and other important statistics about radon levels in the housing stock.

The main findings of the NRRS [XII–1] are as follows:

— Although most dwellings in the USA have relatively low annual average radon levels, a significant percentage of dwellings have levels that are much higher than ambient radon concentrations. The median ambient outdoor radon level is about 0.4 pCi/L (14.8 Bq/m$^3$)[2]. Around 64% of all dwellings have annual average radon levels below 1 pCi/L, and of the remaining dwellings, 20% have concentrations of between 1 and 2 pCi/L and 16% have concentrations greater than 2 pCi/L.
— A disproportionate share of radon exposure is in homes at higher levels. About 56% of the public's residential exposure to radon occurs in homes above 2 pCi/L.
— The annual average radon concentration in the US housing stock is 1.25 pCi/L.
— About 6% of US homes have annual average radon levels greater than 4 pCi/L. This radon concentration is the action level at which the EPA recommends that homeowners act to reduce the levels of radon in their dwellings.
— About 0.7% of US homes have annual average radon levels greater than 10 pCi/L.
— Apartments or condominiums above the second floor seldom had radon concentrations above the EPA's action level.
— Single family detached homes are four times more likely to require mitigation actions than multi-family homes.
— Every EPA region has a significant number of homes that need radon mitigation, although some regions have much greater percentages of homes over EPA's action level of 4 pCi/L.

More details on these and other findings on radon levels in the housing stock are provided in Appendix B of the NRRS summary report [XII–1].

### XII–3.2. Household characteristics

The EPA wanted to determine the relationships between selected housing characteristics and radon levels indoors. Two research objectives were established: to identify characteristics of housing unit construction and

[2] 1 pCi/L = 37 Bq/m$^3$.

characteristics of heating, ventilation and air-conditioning systems associated with radon concentrations in housing units in the USA, and to ascertain their relative importance in explaining the variations in radon concentrations in the housing stock [XII–1]. This information was collected by questionnaire.

The EPA examined the relationship between 50 different characteristics of dwellings (independent variables) and radon levels indoors specified in different ways (dependent variables). The location of dwellings in areas considered to have high, medium and low radon potential was used as an independent variable in one set of analyses and excluded from another. This was because it allowed the EPA to better determine what other factors might be important in contributing to the radon levels that were found in a dwelling.

The initial analysis suggests that the most important predictor of radon levels is the geographic location of the dwelling. It also suggests that housing construction has more of an influence on radon concentration than characteristics of heating, ventilation and air-conditioning systems.

The variables that were found to have the most predictive value in the analyses included the radon potential of the area, whether a dwelling was a single family unit, whether a dwelling had a basement entrance inside the residence, the number of gas appliances used in a residence, whether a dwelling had a basement, and others.

Owing to the uncertainty in the many factors contributing to radon related risks, and on the basis of the NRRS estimate of an annual average radon level of 1.25 pCi/L, the EPA estimated that radon indoors in dwellings causes between 7000 and 30 000 deaths due to lung cancer per year.

## XII–4. FOLLOW-UP ACTIONS

There has been extensive action on radon levels in the USA since the original report:

— The national radon programme was launched and continues to operate, with many successful state radon programmes.
— A series of American National Standards Institute (ANSI — the US standards organization associated with the International Organization for Standardization (ISO)) standards of practice in radon testing and mitigation has been established.
— A state grants programme has been created.
— Extensive ‘consumer outreach’ has been conducted.
— Substantial progress has been made on creating building codes addressing radon.

— Most importantly, millions of dwellings with high radon levels have been remediated and new dwellings have been built with radon reducing features.

All in all, about 1000 lung cancer deaths attributable to radon exposure are avoided in the USA each year because action has been taken in dwellings.

## XII–5. POST-SURVEY CONSIDERATIONS

What worked well for the EPA was taking time on the quality of design and the statistical power of the radon survey. The biggest problem, however, is that it led to the creation of a map of the national radon potential which, while valuable, tended to create a communication problem in relation to radon reduction efforts.

In essence, it gives a false sense of 'relief' for those residents in the lower risk zones; in reality, dwellings with high radon concentrations are found in all areas. Even in low risk areas, the risk is substantial compared with risks associated with many other environmental issues or public health issues.

The only way to know if a dwelling has high radon levels is to test for them, not to look at a map or to learn the concentrations in neighbouring dwellings.

## REFERENCES TO ANNEX XII

[XII–1] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, National Residential Radon Survey: Summary Report, EPA, Washington, DC (1992).

[XII–2] NERO, A.V., SCHWEHR, M.B., NAZAROFF, W.W., REVZAN, K.L., Distribution of airborne radon-222 concentrations in U.S. homes, Science **234** (1986) 992–997.

[XII–3] UNITED STATES CENSUS BUREAU, 1990 Census of Housing: Detailed Housing Characteristics, United States Census Bureau, Washington, DC (1990).

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