Radon Monitoring and Control of Radon Exposure

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Abstract: Typically over 50% of the worldwide collective dose from ionising radiation is due to radon-222 (radon), a decay product of uranium-238. Because it is a gas, radon can move through soils and can accumulate in buildings such as houses, schools and workplaces. This paper describes the mechanisms by which radon can enter buildings and summarises the epidemiological evidence linking radon exposure to lung cancer, including consideration of the synergistic effect of smoking. The components of a national programme to measure and reduce indoor radon are discussed. The authors propose a dual approach to radiation protection: reducing individual risk by identifying and remediating existing buildings with the highest radon concentrations while at the same time reducing collective dose through the radon proofing of new construction. Finally, a number of different radon measurement techniques are described and the advantages and disadvantages of each are discussed.

1. Introduction

1.1. Characteristics of Radon

There are three radioisotopes of radon naturally present in the environment. These are radon-222 (from the uranium-238 decay series), radon-220 (from the thorium-232 decay series) and radon-219 (from the uranium-235 decay series). Uranium-235 represents a small fraction of the activity of natural uranium. The production of radon-219 is therefore low and this, along with its short half-life of 54s, means that this radioisotope is of minor radiological significance. While the concentrations of thorium-232 in the environment are often similar to or higher than those of uranium-238, radon-220 has a shorter half-life (56s) than radon-222 (3.82 days). This means that radon-222 can migrate over much greater distances after production than radon-220. The isotope radon-222 produced in the soil is often the principal source of radon in indoor air, while radon-220 is normally only of concern from a radiation protection viewpoint if high concentrations of thorium-232 are present in the interior surface construction materials of a building.

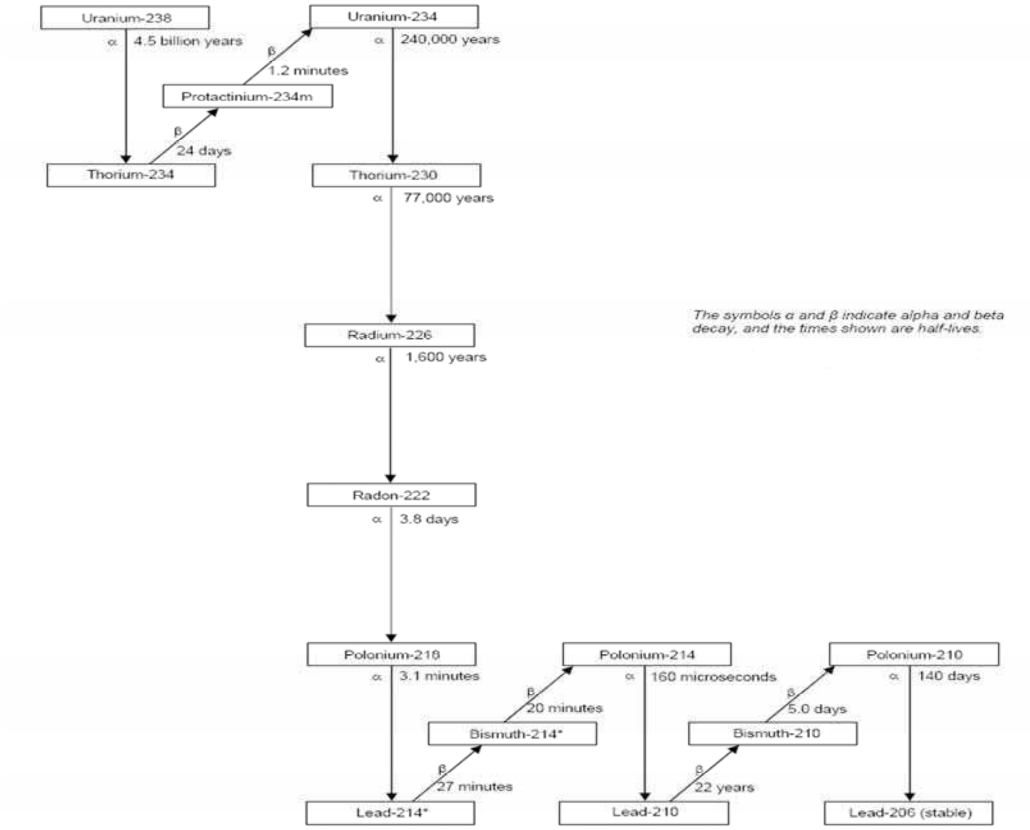
This paper will therefore focus on radon-222, which will be referred to as radon throughout the text. The uranium-238 decay series will be referred to throughout the text and is shown in FIG. 1.

While radon is a component of the uranium-238 decay series, it is produced directly by the radioactive decay of radium-226. Both uranium and radium are present in variable quantities in all rocks and soils. Radon is colourless, odourless and tasteless and can only be measured using special equipment. Because it is a gas, radon can move freely through the soil enabling it to enter the atmosphere. When radon surfaces in the open air, it is quickly diluted to harmless concentrations, but when it enters an enclosed space, such as a building, it can sometimes accumulate to unacceptably high concentrations.

An important characteristic of radon is that, like both uranium and radium, it is soluble in water. Ingestion of dissolved radon will result in a radiation dose to the lining of the stomach. However, a definitive link between consumption of radon-bearing water and cancer has not been established.

Inhalation of radon gas that has been released from tap water will contribute to the radon content of indoor air. On average this contributes less than 3% to the collective dose from radon [1] but for certain groups of the population, radon in ground water can be their principal source of their exposure to radon [2]. Radon dissolved in underground streams and waterways can be transported over large distances from the point of production and, when released, can enter buildings immediately above. The uranium and radium concentrations of soils are not therefore always a good indicator of the potential for high indoor radon concentrations to be found in a given area.

FIG. 1. Uranium-238 decay series



1.2. Radon in the Indoor Environment

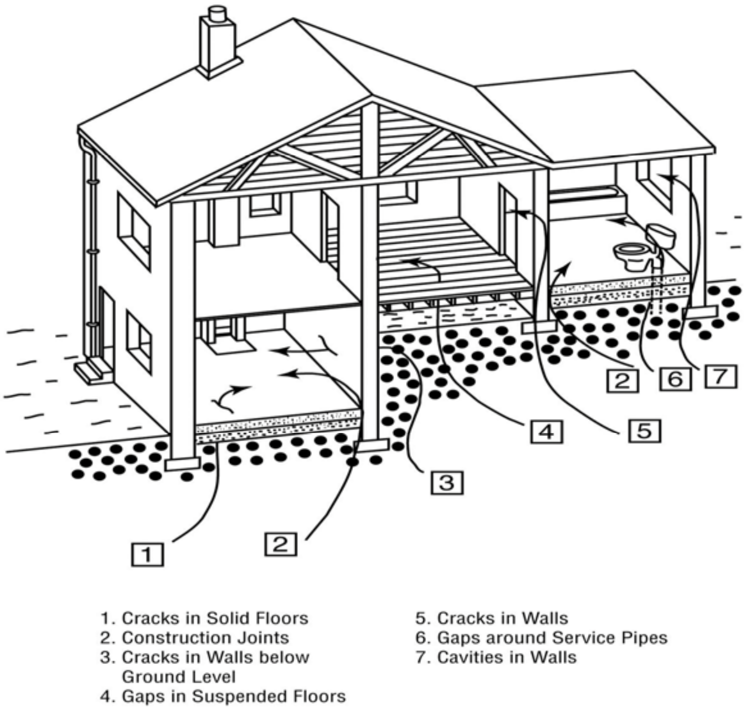
Radon can enter a building from the ground through small cracks in floors and through gaps around pipes or cables. Radon tends to be sucked from the ground into a building because the indoor air pressure is usually slightly lower than outdoors. This pressure difference occurs because warm indoor air is less dense than outdoor air. Typical entry routes of radon into a building are shown in Fig. 2.
Radon decays to form tiny radioactive particles, some of which remain suspended in the air. When inhaled into the lungs these particles are deposited in the airways and attach themselves to lung tissue. They may damage cells in the lung and this increases the risk of developing lung cancer.

Radon is classified as a Group 1 carcinogen by the International Agency for Research on Cancer (IARC), a part of the World Health Organisation (WHO). This means that there is direct evidence from human studies to support the link between exposure to radon and the induction of lung cancer. Although there is evidence that exposure to high indoor radon concentrations can also give rise to significant radiation doses to the skin [3], epidemiological data provides little evidence for increased risks of mortality from cancers or any other diseases other than lung cancer.

1.3. Variability in Indoor Radon Levels

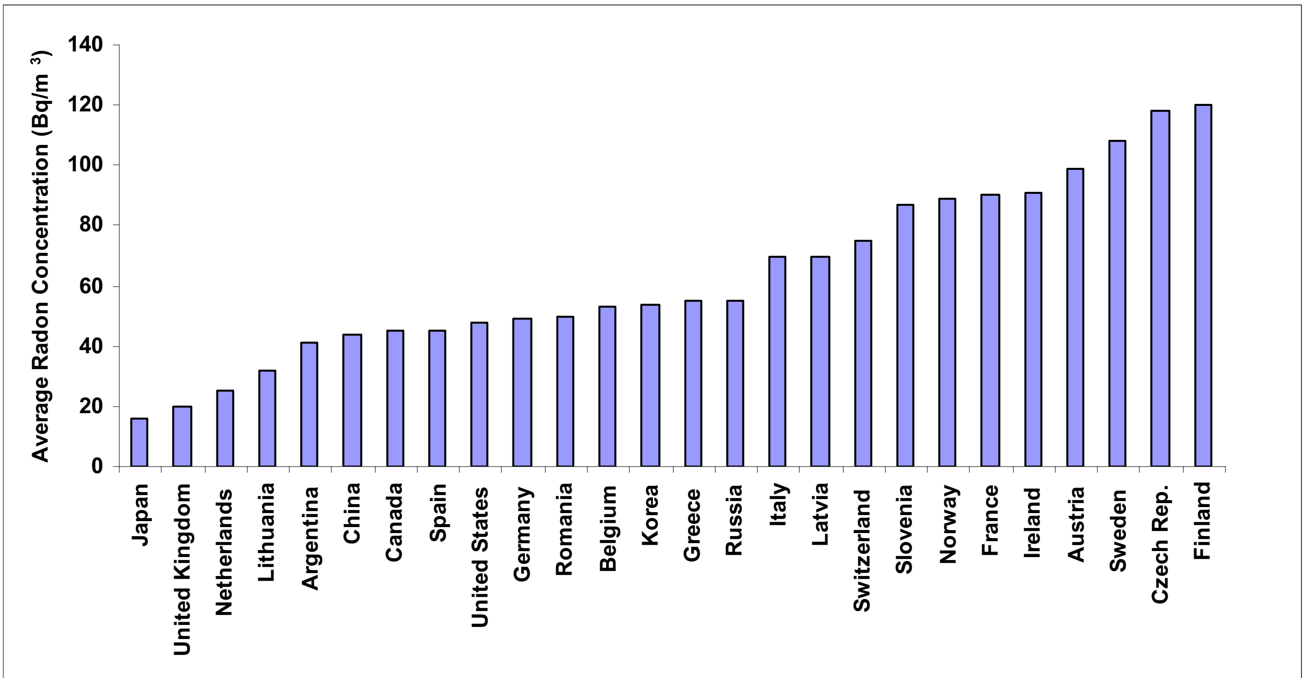
UNSCEAR [1] reports a population-weighted worldwide average radon concentration in homes of 39 becquerels per cubic metre (Bq/m^3). The WHO [4] has recently published a recent review of radon policies in 26 countries. The national average radon concentrations for the 26 countries included in the WHO review are shown in FIG. 3.

FIG. 2. Typical radon entry routes into a building



It should be noted that large variations in indoor radon concentrations are commonly found within countries and these are not adequately described by a single value average. Indoor radon concentrations two or three orders of magnitude higher than the average have been reported in many countries. Indoor radon concentrations usually follow a log-normal distribution and this accounts for the wide variability in concentration observed in indoor air. Variability can be observed between regions, within regions and from building to building within individual towns and villages.

FIG. 3. Average radon concentrations in 26 countries



The average annual effective dose world-wide from radon represents about half of the average annual effective dose from all sources of natural radiation [1]. This varies from country to country, and in countries with particular high average radon concentrations, radon can be the predominant source of all exposure to ionising radiation. As referred to above, certain individuals can receive doses from radon that greatly exceed the average values for the population. For example, in Ireland, where the average annual dose from radon is 2230 μSv [5], one house has been identified with an average radon concentration of 49,000 Bq/m^3, corresponding to an annual dose of about 1.2 sievert [6].

2. Health Risks from Radon

2.1. Historical data

The association between radon exposure and lung cancer has been documented in underground miners in central Europe since 16th century. In the last 40 years, several epidemiological studies have been conducted on uranium and other miners who were occupationally exposed to radon, primarily in Canada, the former Czechoslovakia, Sweden and the United States. These have been reviewed in detail elsewhere [7]. One of the largest of these studies, involving over 2,700 lung cancer deaths in 68,000 miners who between them had accumulated 1.2 million person-years of exposure, was carried out in the United States and published in the 1990s [8].

In attempting to apply the risk estimates from the miners' studies to the general population, several differences between the two groups have to be considered. These include differences in age and sex distributions, the longer period of time over which members of the public are likely to be exposed and differences in the physical environment between mines and residential buildings. While the miners' data proved conclusively that long-term exposure to radon increases the risk of lung cancer, it was recognised that the many differences between miners and the general population could influence the risk factors for both groups. However, in order to get some estimate of the radon problem in homes, the authors of the US miners study concluded that, on the assumption that these data could be applied directly to radon exposure in the home, radon may be responsible for approximately 9% of all lung cancer deaths in the United States.

Since the miners' studies were undertaken, several case-control studies have been conducted to directly quantify the risk following exposure to radon in the home [9-11]. A number of these studies were of low statistical power and, as a result, the calculated risk factors have large uncertainties. However, the risk factors derived are still broadly consistent with the miners' data. In 1999, an extensive study by the US National Research Council estimated that 10-15% of all lung cancers in the United States are caused by radon [12].

A number of geographical correlation studies [13, 14] have also investigated the relationship between the risk of lung cancer and exposure to radon in the home. These studies compare exposure to radon and the incidence of lung cancer across large groups of the population and assume that the same risk relationship exists at the individual level. With this approach it is almost impossible to properly account for confounding factors that could influence the observed incidence of lung cancer. The most important confounding factor is smoking which can also show significant geographical variation and it is impossible to separate the risk due to smoking from that due to radon unless the smoking status of each affected individual is known. For this reason these types of studies are normally not considered to provide useful information on the risks associated with exposure to radon [15].

2.2. Most recent data

In December 2004, the results of a joint analysis of 13 individual studies of residential radon exposure in nine European countries were published [16]. These studies had been carried out in Austria, the Czech Republic, Finland (2), France, Germany (2), Italy, Spain, Sweden (3) and the United Kingdom. The size of each of these studies on its own is too small to provide statistically significant results, but when combined they give important information on the health effects of exposure to radon in homes.

The study analysed 7,148 lung cancer cases and 14,208 controls. The principal conclusion reached was that, while the underlying lung cancer risk for active smokers was considerably higher than for lifelong non-smokers, the risk to both groups increased by approximately 16% for every 100 Bq/m^3 of radon exposure in the home. In addition, the risk seemed to apply even at relatively low radon exposures; i.e. below the Reference Levels that apply in a number of countries (see section 3.4). In early 2005, a comparable study undertaken in the United States reported similar results [17]. The results of both studies provide risk factors for radon exposure in the home that are consistent with those derived from the earlier studies on miners occupationally exposed to radon.

It is known that at high radiation doses a linear relationship exists between radiation exposure and the risk of developing cancer. For radiation protection purposes, it is assumed that the linear relationship also applies at much lower doses. This is called the Linear-No-Threshold (or LNT) Hypothesis. In the case of radon, the LNT Hypothesis appears to hold down to about 150 Bq/m^3. Below this concentration, there is no conclusive evidence either way.

2.3. Links between radon and smoking

It is generally accepted that radon is the second most important cause of lung cancer after tobacco smoking. It has previously been shown [18, 19] that the relationship between exposure to radon and tobacco smoking is greater than the sum of the individual risks, but less than multiplicative. These data were derived from studies of miners exposed to radon and until recently no study of radon exposure in the home provided strong information on the risks from radon in combination with smoking.

The recent European study recorded detailed smoking histories for all individuals and that allowed the relationship between smoking and radon to be examined [16]. The study found that, on average, the risks of contracting lung cancer before age 75 at radon concentrations of 0, 100, 200 and 400 Bq/m^3 for lifelong non-smokers are 0.41%, 0.47%, 0.55% and 0.67% respectively. For active smokers, the corresponding rounded values are 10%, 12%, 13% and 16%. Therefore the risk to active smokers from radon is approximately 25 times greater than the risk to lifelong non-smokers. Ex-smokers were also found to be at significant risk from radon for a number of years after they had stopped smoking. This suggests that the majority of lung cancers due to radon will be observed in people (active smokers but also ex-smokers) whose lungs have already been damaged by tobacco smoke.

3. National Radon Programmes

3.1. Introduction

Protecting the public against indoor exposure to radon is both a radiation protection and a public health issue. As such, the implementation of an effective programme may involve several different national organisations such as those involved in radiation protection and public health policy, public and private bodies specialising in radiation measurements and bodies that set and implement building control standards. Typically, the lead organisation at national level has been the organisation responsible for radiation protection.

A national radon policy should consist of a number of key components

- A national survey to determine the distribution of radon levels in buildings;
- The identification of areas with higher than average radon concentrations (often referred to as 'Radon Prone Areas' or 'High Radon Areas');
- The setting of a national reference level for radon in homes and workplaces and the incorporation of the reference level into national legislation, where appropriate;
- The promotion and enforcement of building control measures to limit radon build-up in new homes;

- A programme to identify and remediate those buildings with the highest individual radon concentrations;
- A training programme for professionals working in the building, radon measurement and radon remediation sectors; and
- A focused public information and awareness programme.

These seven components are addressed below.

3.2. National Radon Surveys

Each country should evaluate the degree to which the population is exposed to indoor radon. While the principal focus will be on houses, which represent the greatest number of buildings, consideration also needs to be given to assessing radon concentrations in workplaces, both above and below ground. In several countries the distribution of radon in schools has received special attention because of the large number of individuals potentially exposed and the age at exposure.

In undertaking a national survey of radon in homes, there are two principal considerations.

These are

- The need to estimate the average exposure of the population to radon, and the range of exposures occurring, for comparison with exposures to other sources of ionising radiation and with other public health risks. This can be achieved by measuring radon in randomly selected homes [7]; and
- The need to identify areas where higher than average radon concentrations are likely to be found. This can be achieved by carrying out a geographically-based survey. The results obtained can be used to develop radon risk maps and to identify Radon Prone Areas.

Statistical expertise is needed in the design of such surveys but with careful planning a single survey can be designed to address both issues simultaneously. The results obtained will define the extent of radon exposure and will provide the basis for future decisions on development and implementation of a national radon policy. Measurements protocols for national radon surveys are discussed in section 4.

The surveys described above show the variation in indoor radon concentrations, irrespective of the source of the radon. Where high indoor radon concentrations are found, the ground immediately below is typically the principal source. In some cases, there can also be a significant contribution from radon released from the construction materials of the house and/or from the domestic water supply. Separate surveys may be needed to quantify the contribution from these latter two sources.

Because of the differences in construction and ventilation of workplaces compared to homes, the distribution of radon in workplaces may be very different to that found in homes. Separate surveys of the distribution of radon in indoor workplaces should ideally be undertaken. These surveys should be representative of all indoor workplaces in the country in question and should seek to identify particular features of workplaces where either higher or lower than average radon concentrations might be expected. For example, underground workplaces or workplaces with poor ventilation might be expected to have higher than average radon concentrations. For workplaces that are broadly similar in construction to homes, i.e. small offices and shops, the data derived from the national survey of radon in homes may be useful in the first instance to help target workplaces in Radon Prone Areas.

In the case of schools, large variability can be observed in the radon concentrations in rooms within the same school as well as between schools and this also needs to be taken into account when devising surveys of schools [20].

3.3. Identification of Radon Prone Areas

Upon completion of the national radon survey, the distribution of radon on a regional basis will be known. This will allow identification of Radon Prone Areas i.e. those areas where higher than average radon concentrations are likely to be found and where the probability of finding high individual radon concentrations is increased.

Decisions on the designation of Radon Prone Areas are complex and many factors need to be taken into account. These include the national average radon concentration, the national Reference Level, the actions that will be required in these areas and the availability of resources. In the UK, for example, a Radon Prone Area is defined as an area where it is predicted that one percent or more of the homes will have an average radon concentration above the UK Reference Level of 200 Bq/m^3; in Ireland, the corresponding definition is areas with ten percent or more of homes above the Irish Reference Level 200 Bq/m^3 [7]. The different definitions of Radon Prone Areas reflect the different distributions of radon in the two countries.

Once Radon Prone Areas are identified, there is a need to define specific measures to be applied within these areas. It's worth noting also that as more radon measurement results become available, the areas so designated may need to be amended.

The purpose of defining Radon Prone Areas is to allow efficient targeting of resources. For example, information, advice and measurement campaigns targeted at Radon Prone Areas are likely to lead to the identification of more houses with high radon concentrations than campaigns directed at areas where the predicted percentage of houses with high radon concentrations is low. It may also be more cost effective to require the installation of radon preventive measures in new houses in Radon Prone Areas only, rather than in all new houses.

3.4. Setting Radon Reference Levels

An important element of a national radon policy is the setting of reference levels for radon exposure in homes and workplaces. A reference level is not a strict divide between safety and danger – rather, it represents a level of risk at which the need to reduce radon exposure needs to be considered.

In deciding on the appropriate reference level for exposure to radon either at home or in the workplace, three important factors need to be considered

- How does the reference level compare with both the average and range of radon concentrations in the country? It makes little sense to set the reference level so high that virtually all buildings have radon concentrations below it or so low that virtually all buildings exceed it;
- What level of risk of lung cancer corresponds to the reference level chosen? Given that tobacco is the principal cause of lung cancer, the smoking habits of the population may need to be considered; and
- How does the risk at the reference level chosen compare with other general or occupational risks in society? Exposure to radon can be considered an everyday risk in that we choose to live and work in buildings.

Data on everyday risks in Spain have been published by Colgan [21]. These are shown in Table 1 below. Deaths from accidents on the road and in the home represent a level of risk comparable to that from lifetime exposure to radon at 200 Bq/m^3. These can be regarded as voluntary risks which are readily accepted by society because of their associated benefits. However, society does impose restrictions when it perceives the possibility of reducing the number of fatalities. For example, speed and alcohol limits are designed to reduce the number of fatal road accidents.

Table I: Lifetime risks of death from various causes

Cause of Death	Lifetime Risk
All cancers	1 in 8
Alcohol	1 in 40
Accidents – home	1 in 60
Accidents – traffic	1 in 80
Homicide	1 in 1,200
Nuclear discharges	1 in 75,000,000
Lifetime exposure to radon at 200 Bq/m^3	1 in 50
Lifetime exposure to radon at 1 Bq/m^3	1 in 10,000

Because the criteria for setting a reference level vary from country to country, there is no unique value that should be applied. The ICRP [7] has recommended that, for homes, the reference level should fall within the range 200 to 600 Bq/m^3. In the case of workplaces, a higher value that takes account of the smaller number of hours spent at work can be justified and the ICRP recommends a range of 500 to 1,500 Bq/m^3. The ICRP also recommends that the reference level for homes be applied to schools and long-stay institutions such as nursing homes.

A recent review by the WHO [5] has shown that, in practice, most countries have set reference levels for homes in the range 100 to 400 Bq/m^3. Some countries have set lower reference levels for new homes than for existing homes, although most countries have adopted to apply the same level of protection to all householders. Some countries apply both an advisory reference level and an additional, higher, reference level which, if exceeded, requires mandatory action on the part of the householder. For example, in Sweden, the Reference Level is 200 Bq/m^3 but radon concentrations above 400 Bq/m^3 must by law be reduced to below 200 Bq/m^3. Switzerland has a similar policy for radon concentrations above 1000 Bq/m^3, which must be reduced to below the Reference Level of 400 Bq/m^3. Switzerland also places restrictions on the radon concentrations in rented accommodation that are stricter than those applying to owner-occupied homes.

In general, reference levels for radon in workplaces are legally enforceable. The general approach is to seek to reduce the radon level below the reference level. Where this is not possible, for example in certain types of underground workplaces, occupational exposure to radon is limited by reducing the time spent in the workplace.

3.5. Building Control Measures

As in all other areas of radiological protection, the approach to radon exposures has two objectives: to limit and reduce the highest doses (individual risk) and to reduce average doses (collective risk). The first objective may be achieved by the implementation of a programme to find and remediate those homes with radon concentrations above the reference level, with a particular focus on Radon Prone Areas. In addressing the second objective, it is important to realise that, because indoor radon concentrations tend to follow a lognormal distribution, much of the collective dose is received by those exposed at relatively low concentrations (Table 2). The only way to significantly reduce the average radon concentration in the national building stock is to introduce building codes and construction practices that limit the ingress of radon into new buildings. Such changes will, over time, reduce average radon doses and reduce the health impact of radon.

The availability of remediation methods that are effective, reliable, cost-effective and relatively easy to install is essential for a successful national radon programme. The effectiveness of all techniques needs to be proven under realistic working conditions and their long-term effectiveness should also be evaluated. Experience has shown that, when radon reduction technology is being fitted in homes under construction, enforcement of national building codes is essential if a high degree of success is to be achieved [22]. This suggests that regular site inspections should be an integral component of any national radon programme. The methods used to reduce radon concentrations in new and existing buildings are discussed in greater detail in section 5.

Table II. Distribution of collective doses from radon in Ireland due to radon exposure in homes, above ground workplaces (AGWs) and schools

	Percentage of collective dose in		
Radon Concentration	Homes	AGWs	Schools
Less than 200 Bq/m^3	61.7%	55.4%	64.3%
200-400 Bq/m^3	18.7%	16.8%	17.5%
400-1000 Bq/m^3	16.8%	17.3%	11.7%
above 1000 Bq/m^3	2.8%	10.5%	6.5%
Collective dose (manSv)	9400	753	15

3.6. Identification of Buildings with the Highest Radon Concentrations

As previously mentioned, it is often beneficial to focus on Radon Prone Areas in the first place as the most effective means of identifying homes and workplaces with radon concentrations above the reference level. This approach also allows many of the buildings with the highest radon concentrations to be identified. This can be achieved in a number of ways: additional and more detailed surveys to better define the extent of the Radon Prone Area; public awareness efforts such as advertising and information campaigns that encourage employers and householders to carry out radon measurements; and, where reference levels are legally enforceable, a campaign of 'directions' or 'notifications' requiring that measurements are carried out. Targeting of particular areas in this way should also form the basis of a follow-up programme when very high radon levels (e.g. greater than 1,000 Bq/m^3) are measured in individual houses.

As buildings with radon concentrations above the reference level are identified, a graded approach should be taken to their remediation. The responsible authorities should consider recommending that buildings with radon concentrations that greatly exceed the reference level require remedial work more urgently than those with radon concentrations marginally above the reference level, and set a timescale for such work.

In the case of houses, the relevant authorities should consider requiring radon measurement and, where necessary, remediation, at the time of purchasing or sale of homes. Such initiatives increase the number of radon measurements carried out every year and the associated costs are normally only a small fraction of the cost of the house. This is likely to be a highly effective approach in countries where a large percentage of homes are owner-occupied, but in countries with a large rental sector, other initiatives may need to be considered.

3.7. Training of Professionals

The responsible authorities should establish requirements, such as quality assurance or accreditation schemes, aimed at ensuring that all companies providing radon-related services are competent in their respective fields and that their work is undertaken to a high standard. The services to be considered for such schemes include:

- Manufacture of materials and devices to be used to limit radon ingress into buildings under construction;
- Installation of radon reduction technology in buildings under construction;
- Remediation of existing buildings with radon concentrations above the reference level; and
- Measurement of indoor radon in homes, workplaces and schools, including the application of the appropriate measurement technique(s) and interpretation of data.

3.8. Awareness and Public Information

In situations where reference levels are advisory, it is the choice of individuals whether or not to measure for radon and whether or not to take action if high concentrations are found. In such circumstances, the availability of accessible and understandable information to facilitate informed decision-making is central to the success of the national radon programme.

Most countries that have set a national reference level for radon in homes and workplaces also provide information on issues such as radon entry routes into buildings, health risks (including the relationship with smoking), measurement protocols and remediation options [4]. This information is often specifically designed for householders, builders and/or professionals such as architects and engineers. Training courses for remediation professionals are also organised in many countries and in Spain, Sweden and the UK a video on radon, which includes information on remediation techniques, is available.

In the United States, the Environment Protection Agency (USEPA) operates a decentralised network for informing the public about radon. This consists of multiple, highly-respected organisations that deliver radon messages through established channels to various targeted audiences, thereby fostering co-operative partnerships. The operation of the network involves leading organisations that have special expertise, credibility and communications channels to reach target audiences such as doctors, county health officials, public service officials and builder professionals.

Examples of communication channels include the Journal of American Medicine, the American College of Preventive Medicine, American Medical TV and statements by the US Surgeon General. Each target audience becomes a source of information for new target audiences. Thus doctors pass on the message to their patients, local public representatives inform their constituents etc.

Initially, the USEPA's approach focused on the provision of general public information on radon, but more recently, it has opted for more direct strategies. These include continuously providing information to specifically targeted interest groups, prioritising reduction of the highest radon concentrations (which represent the greatest individual risk), promoting radon-resistant new construction, supporting testing and mitigation in connection with real estate transactions and providing information to the public to allow them make knowledgeable decisions with regard to radon. Information on competent measurement and mitigation firms (updated lists of firms, trained and qualified contractors to test or fix houses etc.) is also readily available. The objective is that the householder receives a consistent message on radon from a number of key sources through multiple channels that will repeat and reinforce the need for individual action.

In additional to the US, a number of other countries have moved from simply providing advice to delivering messages that encourage action. This is because the take-up of radon measurements following information and advertising campaigns is often less than 25%, even when the campaign is focused locally. In this regard, maximising the use of local media (newspapers and radio) is an approach that has proven successful in dealing with other issues.

4. Radon Measurement Techniques

4.1. Introduction

As shown in Fig. 1, radon produces several radioactive 'daughters' which are also present in indoor air. The health risk from inhaling radon and its daughters will depend on the mixture of radionuclides present in the air. Of particular importance are those nuclides which emit alpha particles, since they cause the greatest biological hazard.

Studies have shown that measurements of the concentration of radon gas in indoor air generally provide a good indicator of the risk. Therefore, in most cases, it is not necessary to consider the mixture of radionuclides present in the air – the associated radiation doses can be estimated from the concentration of radon gas alone. This may not be the case for certain complex working environments such as mines, but even then, certain assumptions are made about the ratio between radon and its daughters. While this approach introduces some uncertainly into the conversion from radon concentration to dose, it is the only realistic and practical approach to radiation protection when large numbers of buildings need to measured.

An increased risk from exposure to radon involves exposure over several years. Radon is also known to vary significantly from season to season, from week to week, from day to day and even from hour to hour. The best measure of lifelong risk is therefore a measurement that gives the best estimate of the long-term average radon concentration in a building. This has to be balanced against the need to provide results to employers and householders within a reasonable timeframe so that any necessary remediation can be carried out promptly. Typically, the duration of such a "long-term" measurement will be about three months.

There are situations in which measurements of a few days can be useful. These are referred to as "short-term" measurements. One example is when a building has been remediated and an immediate confirmation that the remediation work has been successful is desirable. In the United States, short-term measurements are sometimes used in real estate transactions (purchase and sale of properties) under "closed house" conditions [23].

The third general type of radon measurement is referred to as an "active" measurement. This involves sampling the air present in a building on typically an hourly basis so that the variability in indoor radon concentrations can be observed. This is most often used as a research tool to assess the impact of environmental parameters such as temperature, barometric pressure etc. on indoor radon. Active radon measurements are seldom a practical tool in assessing the long-term average radon concentration in a building.

For epidemiological studies, it is necessary to estimate the cumulative radon exposure of individuals over their lifetime. Radon measurements made in the house in which the individual currently lives are unlikely to provide a realistic estimate of the previous exposure and it may not always be possible to measure the radon concentration in homes previously occupied by the same individual. Even if such measurements were possible, modifications to the homes in question (for example, extensions or new flooring) or to the way in which the houses are currently used (for example, greater or lower levels of ventilation) can give rise to significant differences between the radon concentration measured today and that which might have been measured previously. A new technique called 'retrospective' radon measurement is currently being developed to address this problem.

One final consideration is that national guidance specifying the radon measurement techniques and protocols to be used within a country or region will be required. This is particularly important to ensure radon measurements are reliable and comparable within the country and that accurate comparisons to the Reference Level are consistently made.

A detailed review of radon measurement techniques can be found in a paper by George [24].

4.2. Long-term Radon Measurements

As mentioned above, an estimate of the long-term average radon concentration is needed in order to assess the associated health risks. Ideally, radon measurements would take place over a full year to avoid any seasonal variations that may exist. However, detectors may be lost if left in a building for such a long period. There can also be technical problems of detector 'fading' which can result in an underestimation of up to 15% in the actual average radon concentration present [25]. It can also be difficult to persuade employers and householders that something that takes a year to measure can be doing them harm. For these reasons, measurements are usually made over a period of two to three months, and the annual average radon concentration estimated using correction factors based on typical seasonal variations [26].

One of the most common radon detectors used for long-term measurements is referred to as a 'track-etch' detector. It consists of a small piece of plastic placed in a small container which is air-tight. Radon gas diffuses into the container and decays, emitting alpha particles which leave invisible damage in the plastic. When the device is returned to the laboratory, the plastic is chemically treated to reveal and enhance the so-called 'pits' or 'tracks' caused by the alpha particles. The number of tracks present is counted under a microscope. The density of pits is directly related to the radon concentration to which the detector was exposed. The most commonly used plastic are poly-allyl-diglycol carbonate (PADC or CR39) and cellulose nitrate (LR-115).

WHO report that use of alpha track detectors (ATDs) which use CR39 is the most commonly used radon measurement technique in 27 of the 33 countries surveyed.

ATDs have the advantage of being small, cheap, simple to use and require no external power source to operate. They can be distributed by post together with instructions about their placement and return. Two detectors are normally used for measurements in houses: one is placed in an occupied bedroom, the other in the main living area. In workplaces, it is generally recommended to use one detector per ground-floor office and, in open-plan working areas, one detector per 200 m^2.

An overview of the application of track-etch detectors can be found in Durrani and Ilic [27].

4.3. Short-Term Radon Measurements

The two most common types of detectors used are activated charcoal detectors (ACDs) and electret ion chambers (EICs).

ACDs are measurement devices used to measure radon over a continuous period of one to seven days. The principle of operation is that the radon adsorbs onto the activated carbon. At the end of the measurement period, the detector is sealed and returned to the measurement laboratory for analysis. Two analytical tools can be used: gamma spectrometry or liquid scintillation counting.

One of the drawbacks of ACDs is that they are highly sensitive to changes in temperature and/or humidity. The devices therefore need to be calibrated over the range of conditions likely to exist in the field. Another concern is that, because of the relatively short half-life of radon, the detectors must be analysed quickly following completion of the measurement and, unlike track-etch detectors, there is no permanent record. The advantage of ACDs is that they are cheap and provide prompt results, but the extrapolation of these results to long-term average radon concentrations is not recommended.

EICs work on the principle that the radon which enters the ion chamber produces radiation which, in turn, ionises the air inside the detector. The negative ions are collected by the positive electret which has been charged prior to being used and which is located at the bottom of the chamber. When returned to the measurement laboratory, the potential difference before and after exposure is measured and the time-integrated ionisation is related to the average radon concentration to which the electret was exposed.

The response of the EIC is not linear in terms of voltage and careful calibration must be applied. Different types of electret and different sizes of chamber are available, suitable for measurements over periods of a few days to a few months. EICs must be handled with care, as dropping them can result in a partial discharge, and an overestimation of the radon concentration. EICs are also sensitive to environmental conditions such as air pressure. In principle, they are not too large to be sent through the post, but their sensitivity, particularly to mechanical shocks, may reduce their practicability.

4.4. Active Radon Measurements

There are several types of active radon monitors available based on the principles of scintillation cells, ionisation chambers or solid state detectors. Active radon monitors collect ambient air using a pump or by allowing it to diffuse into the sensor chamber. Most, but not all, of these monitors measure radon gas only and a filter is used to remove radon daughters and dust from the sampled air.

Active radon monitors usually provide a summary record of the radon concentrations measured over time. A typical measurement period would be one hour, but some of the instruments available on the market allow the sampling time to be set either higher or lower. The measurement is repeated over several successive time periods, allowing the variation in radon concentrations to be determined.

4.5. Retrospective Radon Measurements

The retrospective technique is a passive method that uses CR-39 and LR-115 alpha track detectors to simultaneously measure the surface activity of polonium-210 (Po-210), a decay product of radon, deposited on suitable glass objects in a room by a technique which utilises the different energy responses of both detectors [28]. The LR-115 detector is sensitive to 1.2 – 4.8 MeV alpha particles and will not record the 5.3 MeV alpha particles emitted by the Po-210 implanted in the glass; instead it produces tracks proportional to the intrinsic alpha activity of the glass itself. The CR-39 detector records the tracks due to both the implanted Po-210 surface activity and the intrinsic activity of the glass. The difference in the track density between the two detectors allows for the estimation of Po-210 implanted into the glass by the decay of radon in the room over the time the life time of the glass.

Using the measured polonium-210 surface activity, the age of the glass and the room parameter information (i.e. the average aerosol concentration, ventilation rate etc.) the average radon concentration that the glass has been exposed to can be estimated using a room model programme.

Typical suitable glass objects are those that would have moved from house to house with the occupants and can therefore provide a 'history' of radon exposure. These are most often family photographs of important events such as weddings or christenings that can be very accurately dated.

5. Radon Prevention and Mitigation

5.1. Radon Prevention in Buildings under Construction

Many countries have introduced the mandatory incorporation of radon preventive measures in new buildings. It is much cheaper and easier to incorporate these measures into a new building as it is being constructed than to add them to an existing building. Effective protection of a new building using passive techniques should reduce the need for future concern about radon in the building. Such measures will also reduce the average radon concentrations in the national housing stock, thus reducing the adverse effects of radon exposure on the health of the general population.

A continuous impermeable membrane designed to isolate the building from the ground over the whole footprint of the building is an effective preventive measure. The effectiveness of the membrane is very dependent on the care with which it is installed and, if possible, it is generally desirable for the installation of the anti-radon membrane to be inspected by a building control inspector as part of the routine check during the construction of a new building. The integrity of the membrane is the major consideration in ensuring the building is properly protected.

In addition to a membrane, provision may be made for sub-floor ventilation or depressurisation by means of a ventilated sub-floor void or a sump to extract the radon before it enters the building. If sub-floor ventilation is provided, this will reduce the radon concentration without the need for an extract fan. A sump will not generally reduce radon concentrations unless it is activated by installing an extraction fan. This can be done if testing shows that the radon membrane is not effective. Radon sumps are also used extensively in the remediation of existing buildings with high radon concentrations (see section 4.2.6). In the case of new buildings, many countries advise that radon concentrations should be measured once the building is occupied and, if these exceed the national reference level, that the radon sump be activated by the addition of a fan.

Radon preventive measures in new buildings are generally implemented by means of national building regulations or building codes. One interesting attribute of radon preventive measures is that they will generally be effective in reducing concentrations of other pollutants which would otherwise enter the building with soil gas. This is an important benefit, but one which may be hard to quantify in a formal way.

In some countries soil gas measurements are used on building sites before construction commences so as to provide guidance on whether anti-radon measures should be included. However, this is not the preferred technique in most countries as such measurements are expensive and may not provide an absolute indication that high indoor radon concentrations may or may not arise in the finished building.

5.2. Radon Remediation of Existing Buildings

5.2.1. Introduction

In recent years a considerable body of experience has been accumulated on effective and relatively inexpensive remedial techniques for reducing indoor radon concentrations. Radon remediation works either by preventing the entry of radon into a building from the soil or by removing it after it has entered by means of improved indoor ventilation. The most common remediation techniques include: sub-floor depressurisation (radon sump); increased under-floor ventilation; positive pressurisation; increased indoor ventilation and the sealing of cracks and gaps in the floor and around service entry points.

The most appropriate remediation solution for a particular building will depend on a number of factors including the measured radon gas concentration and the type of building. Through the correct choice of remediation technique it is possible to reduce the radon concentration to well below 200 Bq/m^3 in the vast majority of buildings.

In the case of houses where compliance with the reference level is normally voluntary, some householders opt to undertake radon remediation on a phased basis. This means that the simplest, least expensive solution, which offers reasonable potential for achieving the desired reduction, is undertaken first. Following this the house is retested and, if the radon concentrations have not been lowered sufficiently, then other measures are installed progressively until the required radon reduction is achieved. Alternatively, more extensive and therefore more expensive radon remediation measures may be undertaken to begin with in order to ensure that the radon concentrations will be reduced sufficiently on the first attempt. The phased approach is more likely to be adopted where the householder undertakes the work on a do-it-yourself basis, while specialist contractors will usually take the latter approach.

An overview of the commonly used remediation systems is presented below.

5.2.2. Sealing Floors and Walls

In theory it is possible to prevent radon from entering a building from the ground by sealing all radon entry points such as cracks in solid floors, cracks or openings in ground contact walls and gaps around cables or pipes. In practice, however, effective sealing is often extremely difficult to achieve.

Sealing all possible entry routes involves removing floor covering and skirting boards and then sealing all visible cracks and joints with a suitable sealant. The sealant must be durable and flexible enough to accommodate future movement of building materials. For this method to be successful, effectively all gaps have to be sealed. This is difficult since some gaps may not be visible and over time new cracks and openings may develop. If only 90% of openings were sealed, for example, then radon could enter through the remaining gaps and it is likely that only a slight reduction would be achieved. In practice this method is more likely to be used in conjunction with other methods than on its own.

5.2.3. Increasing Indoor Ventilation

It may be possible to increase the ventilation inside a building by unblocking air vents, providing additional wall vents or by installing window trickle vents. This is an inexpensive remediation solution commonly used in countries with temperate climates. Increasing the ventilation mixes radon-rich indoor air with outdoor air thereby bringing down the radon concentration in indoor air. Increased ventilation also reduces the under-pressure in a building and so reduces the tendency for radon to be sucked into the building from the ground.

Increased background ventilation should only be installed at ground floor level as increasing the ventilation in upper floors may result in higher radon concentrations. This is because increased ventilation on upper floors may cause a stack effect, which draws air up through the building. This remediation solution has the advantage of being fully passive and so does not require long-term maintenance. It may also help to improve indoor air quality generally.

5.2.4. Increasing Under-floor Ventilation

Increasing the air flow beneath the floor can reduce the amount of radon entering the building. This involves the installation of additional sub-floor vents or airbricks or the clearing or replacement of existing ones. Plastic airbricks are now available with a larger open surface than clay airbricks of the same size. The position of the airbricks can have a significant influence on the radon reduction achieved, as dead spaces with no air flow will reduce their effectiveness.

If it is found that the desired reduction in radon concentration has not been achieved, installing a fan can increase under-floor ventilation further. Fans can be installed to blow air into the underground space (supply ventilation) or suck air from the underground space (extract ventilation).

5.2.5. Positive Pressurisation

This method of radon remediation involves blowing air into the building from a specially installed fan unit placed in the attic, thus achieving a very slight positive pressure in relation to outside air. This reduces radon entry due to a pressure effect causing air to be forced out through cracks, joints, windows and openings. Positive pressurisation also has the effect of increasing ventilation and thereby reducing the radon concentration by dilution. Positive pressurisation is best achieved in relatively airtight buildings. If existing buildings are relatively draughty then measures to reduce draughts may be needed to ensure effective pressurisation. It is straightforward to install, requires no major structural intrusion and has the added advantage of reducing condensation problems. However the running costs of such a system are likely to be greater than for an active radon sump.

5.2.6. The Radon Sump (sub-floor depressurisation)

A radon sump is a cavity about the size of a bucket placed in the ground immediately under the floor slab. It is open to the surrounding under-floor hardcore and linked by pipe work to the outside. It operates by reversing the pressure differential between the space under the floor and the room above. The radon-laden air coming from the ground is drawn out from under the slab by an electric fan attached to the pipe work, thus preventing it from entering the occupied indoor space. Using a sump with a fan in this way is known as an active sump.

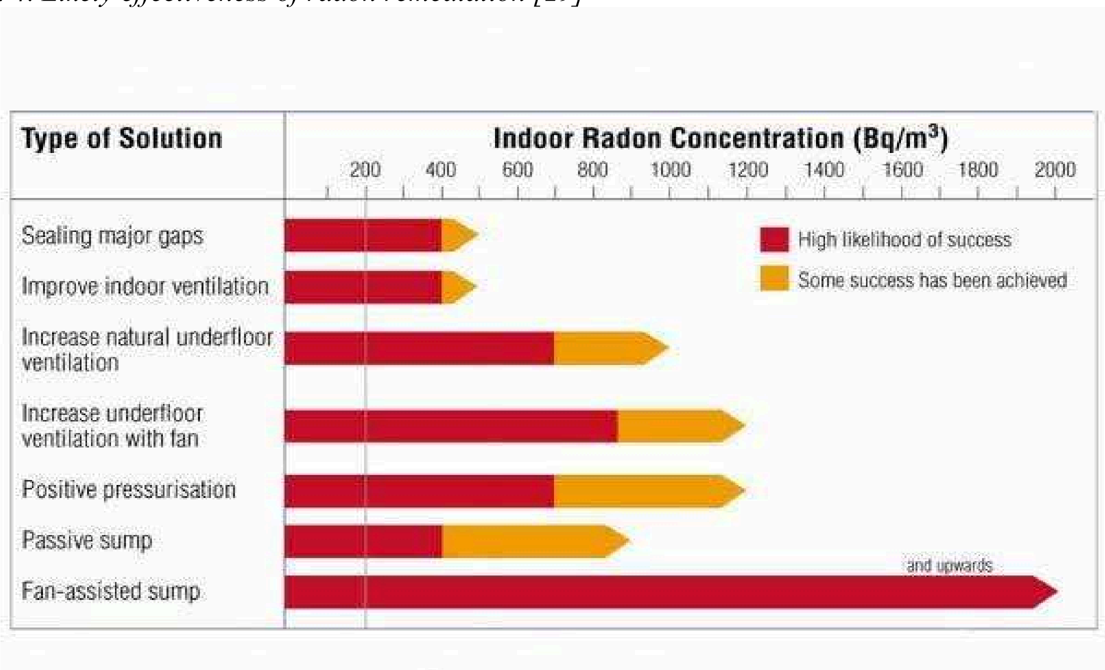
Where a fan is not used the arrangement is referred to as a passive sump. A passive sump has the advantage of having no operating costs and being absolutely silent. However, it is less reliable than an active sump and probably would only be appropriate for radon concentrations up to a few hundred Bq/m^3. Where radon concentrations of several hundred Bq/m^3 or higher are present, the active sump is likely to be the most effective solution. A passive system, if not successful, can be upgraded to an active system by adding a fan.

The number of sumps needed depends on the layout of the building, the floor area and the initial radon concentrations present. As a general rule, a single sump is effective over a surface area of 250 m^2. Several sumps can be linked together and served by the same fan.

5.2.7. Effectiveness of Radon Remediation

Figure 4 summarises the likely effectiveness of the various remediation techniques described above [29]. It can be seen that at radon concentrations of 300 Bq/m^3 any type of remediation is likely to be effective in reducing radon concentrations to below a reference level of 200 Bq/m^3. For concentrations up to about 800 Bq/m^3, while there are a number of different remediation options that might succeed the installation of an active sump or an increase in under-floor ventilation are the options most likely to be successful. For radon concentrations greater than about 1000 Bq/m^3, the installation of an active sump is always the preferred remediation option. Practical experience in reducing radon concentrations in schools in Ireland is summarised in Table 3.

FIG. 4. Likely effectiveness of radon remediation [29]



Effective remediation is very much influenced by the competence of the company undertaking the work. Following remediation to reduce indoor radon concentrations, further radon measurements should always be made to ensure that the work carried out has reduced concentrations to below the national reference level.

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Table III. Observed effectiveness of radon remediation in Irish schools [20].

	Initial radon concentration (Bq/m^3)											
	200-400				400-1000				>1000			
	Reduction factor				Reduction factor				Reduction factor			
System type	No.	mean	min	max	No.	mean	min	max	No.	mean	min	max
Increased background ventilation	175	2.3	0.7	9.1	0	__	__	__	0	__	__	__
Active under-floor ventilation	4	13	1.5	27	6	32	12	49	4	57	29	129
Radon sump	89	9	1.2	33	180	16	1.4	81	61	34	1.6	172
Active under-floor ventilation with other methods	0	__	__	__	3	20	1.8	45	6	64	2.8	141
Radon sump with other methods	15	6.2	2.0	12.	6	11	2.3	25	1	__	__	20

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