National Radon Action Plan

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Abstract

Radon is the leading known cause of lung cancer after smoking. Exposure to radon increases the risk of lung cancer, particularly for smokers. Radon is also the biggest known cause of lung cancer for non-smokers. The majority of lung cancers could be prevented by stopping smoking and reducing exposure to radon. This Action Plan sets out long-term goals and measures to reduce the risk of lung cancer from radon in Finland. It focuses on reducing radon concentrations in indoor air, because radon in indoor air is usually the largest source of radiation exposure. Radon gas found in indoor air is released from the soil and bedrock underneath or surrounding buildings, building materials or borehole water. The Action Plan is based on Article 103 of the Directive laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation (2013/59/Euratom). The Article obliges Member States to draw up a national action plan addressing long-term risks from radon exposure. Finland has fulfilled this obligation by enacting section 159 of the Radiation Act (859/2018). Further provisions on the Action Plan and its content are laid down in the Government Decree on Ionising Radiation (1034/2018, section 54 and Annex 6).

Keywords	exposure, radon, construction, indoor air, cancers		
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Tiivistelmä

Radon on tupakoinnin jälkeen merkittävin tunnettu keuhkosyövän aiheuttaja. Altistuminen radonille lisää erityisesti tupakoivien riskiä sairastua keuhkosyöpään. Toisaalta radon on tupakoimattomien merkittävin tunnettu keuhkosyövän aiheuttaja. Suurin osa keuhkosyövistä voitaisiin välttää lopettamalla tupakointi ja vähentämällä altistumista radonille. Tässä toimintasuunnitelmassa asetetaan pitkän aikavälin tavoitteet ja keinot, joiden avulla radonista aiheutuvaa keuhkosyöpäriskiä Suomessa voidaan pienentää. Toimintasuunnitelman pääpaino on sisäilman radonpitoisuuden vähentämisessä, koska hengitysilman radon on suomalaisille tavallisesti merkittävin säteilyaltistuksen aiheuttaja. Radonkaasu päätyy sisäilmaan joko rakennuksen alla ja ympärillä olevasta maa- ja kallioperästä, rakennustuotteista tai porakaivovedestä. Toimintasuunnitelma perustuu säteilysuojelun perusnormidirektiivin (2013/59/Euratom) 103 artiklaan, joka edellyttää, että jäsenmaat laativat kansallisen toimintasuunnitelman radonista aiheutuvien pitkän aikavälin riskien ehkäisemiseksi. Suomessa tämä velvoite on toimeenpantu säteilylain (859/2018) 159 §:ssä. Toimintasuunnitelmasta ja sen tarkemmasta sisällöstä säädetään tarkemmin valtioneuvoston asetuksessa ionisoivasta säteilystä (1034/2018, 54 § ja liite 6).

Asiasanat altistuminen, radon, rakentaminen, sisäilma, syöpätaudit

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Nationell handlingsplan för förebyggande av riskerna med radon

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Referat

Efter rökning är radon är den främsta kända orsaken till lungcancer. Exponering för radon ökar särskilt rökarnas risk att få lungcancer. Å andra sidan är radon den främsta kända orsaken till lungcancer bland icke-rökarna. De flesta fallen av lungcancer skulle kunna undvikas om rökandet upphörde och exponeringen för radon minskade. Denna handlingsplan innehåller långsiktiga mål och metoder inriktade på att minska finländarnas risk att få lungcancer på grund av radon. Planen fokuserar på att minska radonhalten i inomhusluft, eftersom radon i inandningsluften är den vanligaste orsaken till finländarnas exponering för strålning. Radongas i inomhusluften kommer antingen från marken eller berggrunden under eller kring byggnaden, från byggprodukter eller från borrbrunnsvatten. Handlingsplanen grundar sig på artikel 103 i direktivet om grundläggande säkerhetsnormer för strålskyddet (2013/59/Euratom), som föreskriver att medlemsstaterna ska ta fram en nationell handlingsplan för förebyggande av riskerna med radon på lång sikt. I Finland har denna förpliktelse genomförts i 159 § i strålsäkerhetslagen (859/2018). Närmare bestämmelser om handlingsplanen och dess innehåll finns i statsrådets förordning om joniserande strålning (1034/2018, 54 § och bilaga 6).

Nyckelord	exponering, radon, byggande, inomhusluft, cancersjukdomar		
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Contents

INTRODUCTION

Radon in indoor air is the most significant source of radiation exposure for Finns. Each year, radon is estimated to cause around 300 cases of lung cancer. People can personally influence how much they are exposed to radon at home and at work. However, this requires cooperation between different operators in areas such as risk communication, construction and enforcement. This Action Plan sets out long-term goals and measures to reduce the risk of lung cancer from radon in Finland.

This action plan is based on Article 103 of the Directive for protection against the dangers arising from exposure to ionising radiation (2013/59/Euratom), or so-called BSS Directive, which requires Member States to draw up a national action plan to prevent long-term risks from radon. In Finland, this obligation has been implemented by laying down provisions on an obligation for the Ministry of Social Affairs and Health to draw up a national action plan pursuant to section 159 of the Radiation Act (859/2018). Further provisions on the Action Plan and its content are laid down in the Government Decree on Ionising Radiation (1034/2018, section 54 and Annex 6). The Decree requires updating the action plan at least once every five years.

The Radiation and Nuclear Safety Authority initially primarily prepared this National Action Plan to Prevent Risks from Radon. In 2017, stakeholders were consulted on the action plan. The steering group of the action plan has included a working group consisting of radon authorities. The working group of radon authorities consists of members from the Ministry of Social Affairs and Health (chair), the Ministry of the Environment, the National Supervisory Authority for Welfare and Health Valvira, representatives of the health protection and occupational safety and health areas at regional state administrative agencies, the Association of Finnish Local and Regional Authorities, and the Radiation and Nuclear Safety Authority (secretary).

Jari Keinänen April 2020

GLOSSARY

ALARA Optimization principle (ALARA principle, As Low as Reasonably Achievable).

Exposure. Exposure is a numerical measure of the amount and duration of human exposure to a harmful factor. In the context of radon, exposure is the average radon concentration multiplied by the duration of the exposure period. For example, Exposure of 1,650 hours to the average radon concentration of 300 Bq/$m^3$is equivalent to 495,000 Bqh/m^3. See Radon exposure

Activity, Activity concentration. Activity is the quantity of nuclear transformations taking place in a second. The unit of activity is becquerel (Bq). The activity concentration is the activity per volume or mass unit. For example, the activity concentration of radon (also referred to as radon concentration) is expressed as becquerel per cubic metre of air (Bq/m^3) or becquerel per a litre of water (Bq/l).

Dose. A dose is a quantity that describes the harmful effect of radiation on a body part or the whole body. Its unit of measurement is sievert (Sv). *Equivalent dose* describes the harmful effect of radiation on an organ or tissue. *Effective dose* describes the adverse effect of radiation on the whole body.

In this document, 'dose' means the effective dose.

Dose conversion factor. The factor used to convert the exposure into a dose. The unit of the dose conversion factor is e.g. mSv/(Bq h/m^3).

ICRP. The International Commission on Radiological Protection develops and maintains an international radiation protection system. The ICRP's system of radiation protection is used globally as a joint basis for standards, legislation, official guidelines and programmes as well as good practices. The maintenance and refinement of dose conversion factors is part of the ICRP's activities.

National radon database. The national radon database contains the results of indoor air radon measurements of dwellings, workplaces and other premises used by people that the Radiation and Nuclear Safety Authority (STUK) has become aware of.

Other premises used by people. Other premises used by people include public meeting facilities specified under section 13 of the Health Protection Act and other spaces intended for long-term use. Typically, the number of people spending time in these spaces is larger compared to a dwelling considering the size of the space, and their use is not limited to employees (e.g. day-care centres, schools and sheltered housing).

Radon. Radon refers to the radon isotope radon-222, which has a half-life of 3.8 days.

Other natural radon isotopes, radon-220 (thoron) and radon-218 (actinon), are very short-lived and therefore exist in low concentrations in the indoor air of buildings and no reference levels have been set for their concentrations.

Radon exposure. The product of the radon concentration and the time spent at that radon concentration (E), calculated for each individual using the formula:

$$E = \sum_{i=1}^{n} C_i T_{i,} = C_1 T_1 + C_2 T_2 + \ldots + C_n T_{n,}$$

Where C_i is the radon concentration and T_i is the time spent in that radon concentration and *n* is the number of different workspaces. Radon exposure unit is becquerel hours per cubic metre ($\frac{\mathrm{Bq\,h}}{\mathrm{m}^3}$).

Radon suction pit. A radon mitigation method that involves suctioning air from under a building. This considerably reduces the flow of pore air with radon to the building, reducing the radon concentration in indoor air.

Radon well. A radon mitigation method that involves sucking air from outside the building from a depth of 4–5 m from sandy or gravelly soil. This considerably reduces the flow of pore air with radon content to the building, reducing the radon concentration in indoor air.

Radon piping. A radon prevention method that involves installing drainage pipe under the floor in a layer of crushed stone during the construction of a new building.

Radon risk awareness. The person or party correctly understands the health risk caused by radon and is able to act sensibly, i.e. measure radon levels in relevant spaces, make mitigation when necessary and ensure that the mitigations have been successful by repeating the measurement.

Construction product. A material intended to be permanently incorporated into a building or parts of it and whose properties affect the properties of the building from the perspective of exposing people residing in the building to ionising radiation.

Ordinary workplace. A workplace whose ventilation, temperature, humidity and other physical properties correspond to the interior characteristics of conventional buildings.

ABBREVIATIONS

AVI Regional state administrative agency, Health protection

Bq Becquerel, see Activity.

ICRP International Commission on Radiological Protection

MSAH Ministry of Social Affairs and Health

STMa Ministry of Social Affairs and Health Decree on Ionising Radiation

STUK Radiation and Nuclear Safety Authority

SV Sievert, see Dose.

SätL Radiation Act

THL Finnish Institute for Health and Welfare

TTL Finnish Institute of Occupational Health

TsL Health Protection Act

Valvira National Supervisory Authority for Welfare and Health

VN Government

VNa Government Decree on Ionizing Radiation

VNK Prime Minister's Office

WHO World Health Organization

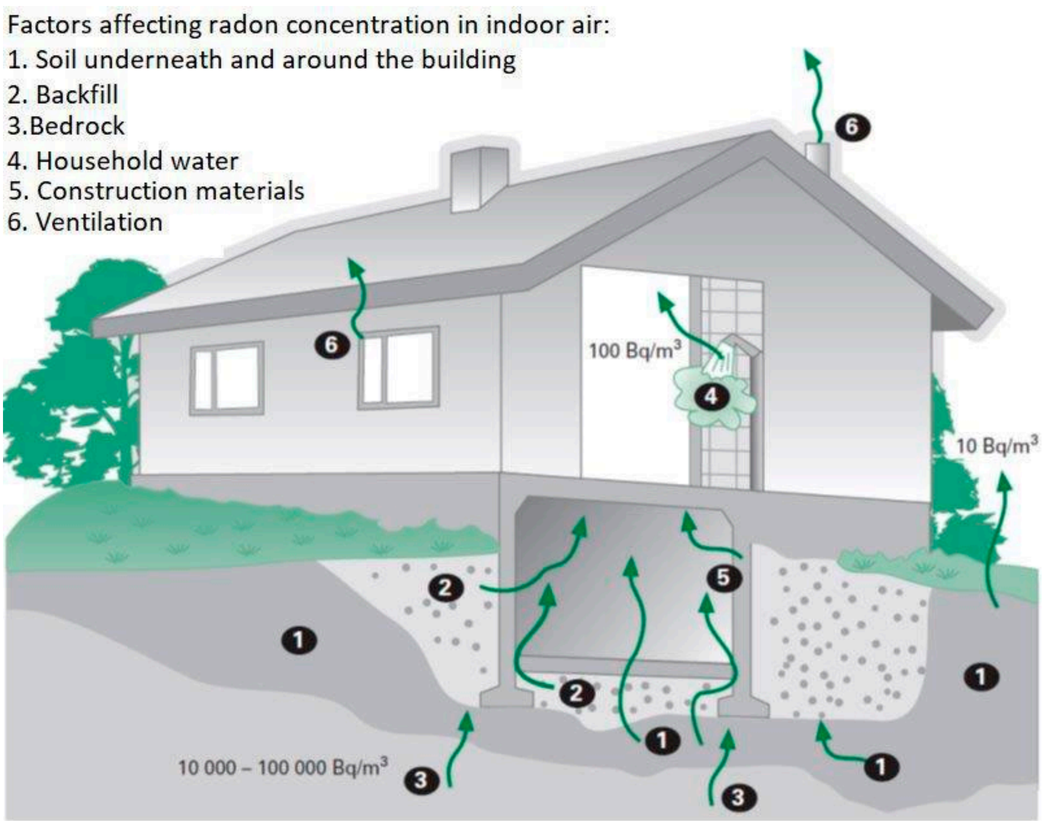
ME Ministry of the Environment

1 Background

1.1 Soil and bedrock as sources of radon in indoor air

Radon (^{222}Rn) is a naturally occurring radioactive noble gas that is continuously formed by uranium in the soil, found in small concentrations in Finland, for example in granite. Radon is transported from the soil to indoor air through gaps in building foundations (Figure 1). Some construction products and household water containing radon also produce radon in indoor air. Finland has one of the world's highest radon concentrations of indoor air in buildings due to the country's bedrock, construction methods and climate.

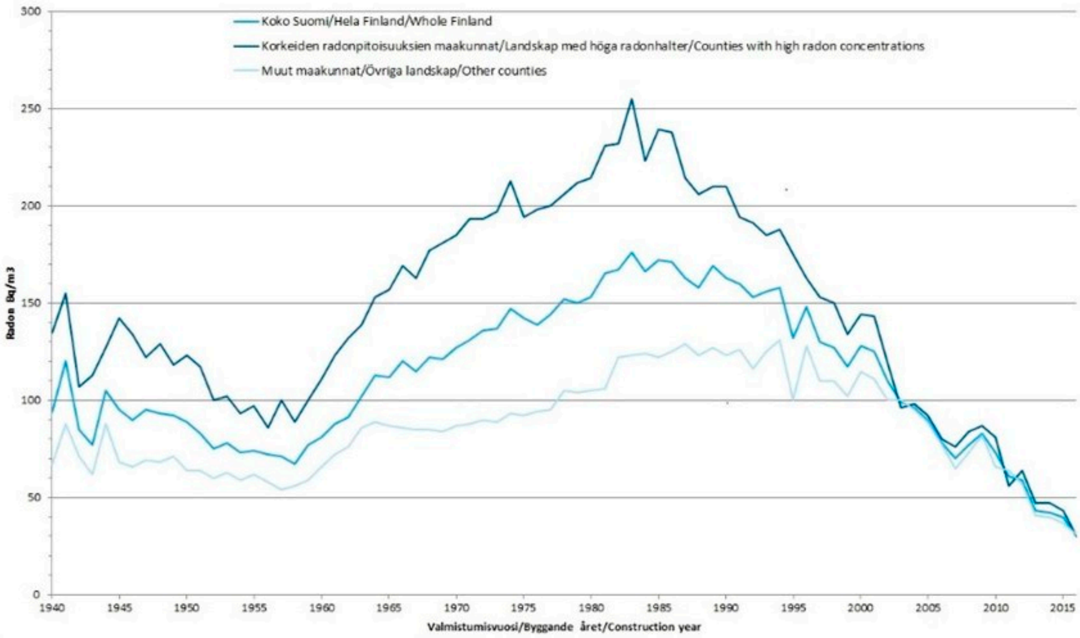
Figure 1. Factors affecting radon concentration in indoor air



Ground-supported floor slab may be a risky base floor structure if the gap between the floor and the wall and the penetrations required by technical building solutions have not been sealed. Significant amounts of radon may also pass through a very dry concrete structure through diffusion (Kettunen 2019). Increased radon concentrations also occur in other base floor structures, but they are less common. The highest concentrations have been measured in buildings constructed on a slope and buildings with ground-supported walls made of lightweight concrete block (Mäkeläinen et al. 2009).

The use of ground-supported floor slabs started to become more common in building construction in the 1960s and 1970s, which was reflected in an increase in the average radon concentration of the housing stock. Meanwhile, a change in construction resulted in denser outer layers of buildings and no attention was paid to the supply of replacement air, which resulted in poorer ventilation in dwellings. Natural ventilation systems were the most common mode of ventilation until the early 1980s. After this, forced ventilation systems became more common; first, exhaustion ventilation and later mechanical supply and exhaust ventilation. Replacement air vents became mandatory in 1987, which reduces the radon of indoor air. From 2004 onwards, almost all new buildings have a mechanical supply and exhaust ventilation system installed due to construction regulations, which reduces radon in indoor air. The first radon prevention studies in new construction were carried out in the 1980s and the first radon prevention guidelines were published in 1993 (Ministry of the Environment 1993). As a result, radon prevention measures were implemented already during the construction stage in areas with high radon concentrations. In fact, radon concentrations in single-family houses began to decrease in the single-family houses built in the mid-1980s, especially in counties with high radon concentrations (Figure 2).

Figure 2. Medians of radon concentrations measured in single-family houses according to the construction year in the provinces with high radon concentrations (South Karelia, Kanta-Häme, Kymenlaakso, Pirkanmaa, Päijät-Häme and former Eastern Uusimaa) and in other counties as well as in Finland as a whole. As the data have been directly extracted from the national radon database, measurements at high radon concentrations are over-represented, as more measurements are carried out in areas known to have high radon concentrations.



The unofficial definition of "high-radon counties", previously used when referring to radon found in housing, should no longer be used, as the regional differences in radon concentrations have disappeared, at least in new buildings. For more information on the measurement requirements for workplaces, see the section Identifying high radon sites and areas.

1.2 Household water as a source of radon in indoor air

In Finland, groundwater and particularly water from drilled wells can be a significant source of radon in indoor air. The radon found in household water causes two different kinds of radiation exposure. Radon that finds its way to the human body from drinking water causes radiation exposure to the digestive system.

Meanwhile, radon is released from water to indoor air, for example when washing dishes and showering. Based on the new research results and modelling summarised in the ICRP 137 report, exposure by inhalation causes a clearly more significant radiation dose than exposure via the gastrointestinal tract (ICRP 2017).

The radon concentration of household water of 1,000 Bq/l causes an average increase of 40 Bq/m^3 in the radon concentration of indoor air. Based on estimates, in 6,000 households, the water from private drilled wells contains more than 1,000 Bq/l of radon (Turtiainen and Salonen 2010). This figure amounts to around 10 per cent of all households using water from drilled wells. In wells cased with concrete rings, radon concentrations exceeding the quality target (300 Bq/l) are highly unlikely, as these types of wells have better ventilation. If excessive radon concentrations are found in well water, there is reason to consider using some other source of water. If it is not possible to use or build an alternative water source, domestic water treatment can be used. Radon can be removed from water either by aeration or by activated carbon filtration.

In water supply plants, radon concentrations in indoor air vary according to the amount of radon emitted from the soil and bedrock, the amount of raw water treated at the plant, and the radon concentrations of water. The radon in raw water is partly released into indoor air when it is in contact with air. Especially in the aeration treatment of water, radon gets easily released into the surrounding air. In the context of treating large volumes of water, a lot of radon is released into the air in the space, even if the radon concentration of the water itself was small.

1.3 Construction products as sources of radon in indoor air

The mean radon concentration in dwellings on the upper floors of blocks of flats is 44 Bq/m^3 (Mäkeläinen et al. 2009). This figure probably also serves as a good example of the radon concentration caused by concrete building materials. Achieving a low radon concentration in indoor air may be more difficult in concrete buildings than in wooden buildings. The radon concentration of some stone houses may be above 50 Bq/m^3 due to the radon production rate of construction materials alone, especially if the stone material contains above-average levels of radium-226 isotope, belonging in the uranium series. Construction material may contain so much radium-226 isotope that the radon emanated from it makes the radon concentration in indoor air exceed the reference levels. As radioactivity in construction products has been monitored since 1993, exceeding the radon reference levels due to radon emanating from construction products is unlikely in Finland (Guideline St 12.2 until 2018 and Radiation Act 859/2018).

1.4 Dose caused by radon

The method of assessing the dose caused by indoor air radon changed in Finland at the end of 2018 in line with the ICRP recommendations (ICRP 2017) when they were published in Appendix 3 to Government Decree 1034/2018. The average dose of Finns has been described using the concept of the mean effective dose. Based on a new dose conversion factor, the mean dose caused by indoor radon in housing is estimated to be 4 mSv/year. The mean effective dose caused by indoor radon in 2012was estimated at 1.6 mSv/year and was based on the previous ICRP dose conversion factor (ICRP 1993). A radon concentration of 300 Bq/m^3 at home causes the annual dose of 14 mSv/year in the dwelling. A radon concentration of 300 Bq/m^3 at work causes the annual dose of 3-4 mSv/year to an employee with a regular job.

The new dose conversion factor does not affect risk assessment, i.e. the number of cancer deaths linked to radon is still assessed based on epidemiological studies, not on the effective dose. Basic control measures at workplaces are also taken based on radon concentration and radon exposure, not on the basis of the dose. However, those workplaces where corrective measures have failed to reduce radon concentration below the reference levels need a safety licence and must make arrangements on regular monitoring of the dose caused by radon. The dose limit of 20 mSv/v is met in regular work already at concentration of 1,800 Bq/m^3. Previously, the dose limit of 20 mSv/v was reached at concentration of 3,800 Bq/m^3. At workplaces requiring a safety licence, the doses employees are exposed to are recorded in the dose register. The reported doses from radon are higher than previously recorded due to the introduction of the new dose conversion factor.

1.5 Radon and lung cancer risk

The radon in indoor air is one of the environmental exposure agents most harmful for public health. According to the current view, most disease burden related to indoor air is caused by radon, fine particles from indoor sources and passive smoking (Hänninen et al. 2018), which increase premature mortality.

The dose conversion factor has been changed to assess the dose from radon in the same way as the effective dose from other forms of radiation. However, the health hazard caused by radon is assessed on the basis of epidemiological studies concerning radon concentrations, not the dose. As a result, the change in the method of calculating the effective dose does not affect the assessment of radon-related lung cancers.

As the majority of the population's radon exposure occurs in homes, lung cancer calculations have concerned the impact of changes in radon concentrations in dwellings on deaths caused by lung cancer. In some workplaces, high radon concentrations will cause a significant increase in the risk of lung cancer unless concentrations are reduced. Cessation of smoking helps prevent the majority of lung cancers associated with radon.

It takes several years or decades for a person to develop lung cancer after exposure. Radon in indoor air is a significant cause of lung cancer among non-smokers. Smoking is the most significant cause of lung cancer, and changes in the prevalence of smoking are visible in lung cancer statistics. The link between indoor radon and lung cancer has been established in several international epidemiological joint analyses around the world (Darby et al. 2005, Krewski et al. 2006, Zhang et al. 2012). The link between radon exposure and the risk of lung cancer is linear without a safe threshold value. The higher the radon exposure, the greater the risk of lung cancer, but even small concentrations pose a minor risk.

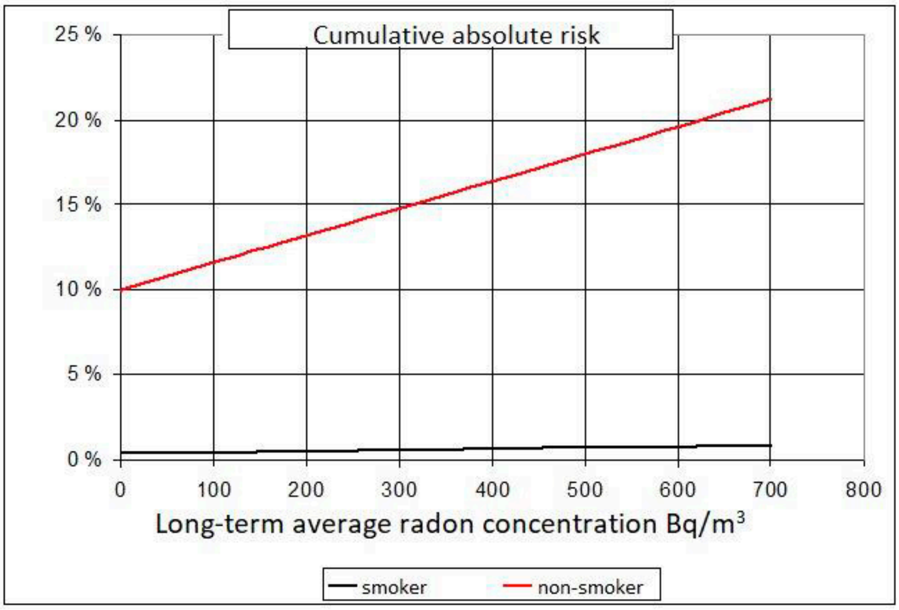
According to a European joint study, the relative risk of lung cancer caused by radon in housing increases by 16% per each 100 Bq/ m^3 (Darby et al. 2006). Based on European studies, radon causes an excess relative risk (ERR) of 0.16 (95% CI: 0.05–0.31) per 100 Bq/ m^3. For miners, the risk assessment differs from the population level estimates; for them, the ERR estimate is 0.12 (95% CI 0.04-0.2) per each 100 Bq/ m^3. The relative risk posed by radon is the same for smokers and non-smokers.

As the life-long risk of developing lung cancer is much higher for smokers (about 10%) than non-smokers (about 0.4%), smokers also have a much higher absolute risk than that non-smokers (Figure 3). The effective dose from radon does not directly reflect the risk of cancer, as the risk depends heavily on the amount a person smokes. The same radon exposure causes up to 20 times higher risk to smokers than to non-smokers.

Decades of exposure at home at a radon concentration of approximately 600 Bq/ m^3 doubles the risk of lung cancer (Darby et al. 2005).

In the European Code Against Cancer, taking action to reduce radon levels in indoor air is mentioned as one of the most important measures people can take to reduce their personal cancer risk (https://www.ilmansyopaa.fi/tunne-syopariskit/ and http://www.europeancancerlea- gues.org/).

Figure 3. The cumulative absolute risk of smokers (upper line) and non-smokers (lower line) of dying of lung cancer by the age of 75 relative to radon levels in indoor air. The relative risk has been presumed to increase by 16% per 100 Bq/ m³ for both smokers and non-smokers. (Darby et al. 2005)



An individual case of lung cancer is presumed to be caused either by tobacco, radon (radon decay products), the interaction of radon and tobacco, or by other causes (e.g. asbestos) (Table 1). Most of the lung cancers caused by radon occur in people who have lived in an environment with radon concentrations below the reference levels, as the majority of the population is exposed to relatively low radon concentrations. In Finland, the radon of indoor air has been estimated to annually cause approximately 40 lung cancer deaths in non-smokers and 240 in smokers (Mäkeläinen 2010).

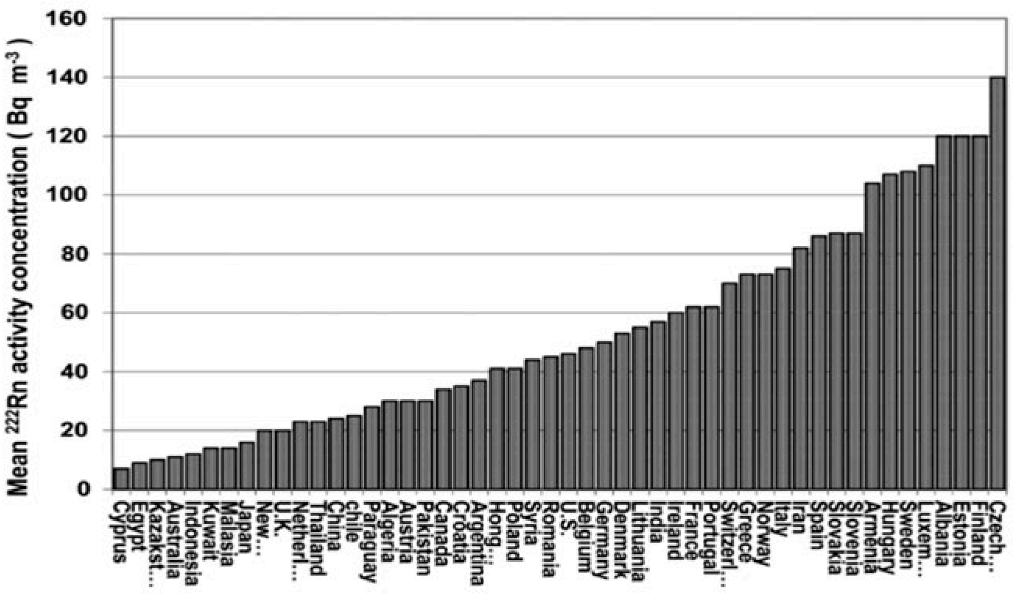
Table 1. Number of lung cancers due to various causes in radon concentration classes (Mäkeläinen 2010).

Radon concentration category Bq/ m^3	Share of population	Share of exposure	Number of lung cancer deaths due to various causes				
			Radon only	Radon and tobacco	Neither radon nor tobacco	Tobacco only	Total
<100	72%	34%	13	82	165	1,073	1,332
100–-199	17%	26%	9	61	40	260	370
200 -299	6%	15%	6	35	14	88	141
300–	5%	25%	9	61	10	67	148
Total	**100%**	**100%**	**37**	**238**	**228**	**1488**	**1991**

1.6 Finland's radon status in an international comparison

Finland's indoor air radon concentrations are among the highest in the world. However, concentrations equivalent to the radon concentrations of indoor air measured in Finland can also be found in some other countries (Figure 4) (Gaskin et al. 2018). In the same publication, 4.1% of all cancer deaths were attributed to indoor-air-related radon exposure in Finland, which is one of the highest shares in the world. However, the publication seems to have used an old estimate of radon concentrations in Finnish houses based on survey from 1991, which is higher than the current estimate.

Figure 4. Average indoor air radon concentration in 50 countries (Gaskin et al. 2018).



2 Long-term targets for reducing the risk of radon-induced lung cancer

The objective of this action plan is to reduce lung cancers caused by radon. The risk of lung cancer from radon can be mitigated by reducing radon exposure and smoking. **Appendix 1 presents recommendations for action to reduce lung cancers caused by radon.**

2.1 Main objectives

Main objectives	Approaches (control responsibility[1])	Indicators
Reducing the number of cases of lung cancer caused by radon	Radon exposure in dwellings and other premises used by people (HPA) and workplaces (STUK) will be reduced. In addition, reducing smoking will contribute to the achievement of the target (Valvira, MSAH).	The extent of radon exposure and prevalence of smoking among the population and employees and related development.

1 building control = municipal building control authority, MSAH Ministry of Social Affairs and Health, STUK =Radiation and Nuclear Safety Authority, HPA = municipal health protection authority, OSH = areas of responsibility of occupational safety and health, Valvira = National Supervisory Authority for Welfare and Health

Main objectives	Approaches (control responsibility[1])	Indicators
Reducing radon exposure	Those undertaking construction projects will take into account radon risks in the design and construction solutions for new buildings subject to a permit (building control). Those undertaking construction projects take into account radon safety and carry out the necessary radon mitigation efforts in connection with renovation and remodelling subject to a building permit implemented due to other reasons (building control). It is essential that those undertaking construction projects are aware of the radon-related risks and hire designers and a contractor with awareness of radon. It is also key that, in connection with the permit process, the building control monitors that the risks related to radon have been appropriately taken into account in the project as part of the safety of construction to the extent required by e.g. construction safety. The owner/holder of the building will take measures to limit radon exposure if the reference levels found in dwellings and other areas exceed the reference values (HPA). The employer limits radon exposure at workplaces if radon concentrations exceeding the reference levels (STUK) have been found at the workplace. The responsible authority will provide advice and, if necessary, oblige the owner, holder or employer of the building to restrict the the exposure.	Radon concentrations in new and existing buildings and the number and efficiency of radon mitigation.

Main objectives	Approaches (control responsibility[1])	Indicators
Raising awareness of radon concentrations in indoor air	Residents of residential buildings or owners or holders of buildings will measure radon levels in single-family houses and dwellings on the lowest floors of blocks of flats across the country. HPA and STUK will provide more information about the need for measurements in residential buildings using the approaches mentioned in the Raising radon risk awareness section. Employers or other parties responsible for premises measure radon concentrations at workplaces and other premises used by people as required by the Radiation Act (STUK, OSH, HPA). Results of the radon measurements are comprehensively recorded in the national database (STUK, MSAH, OSH, HPA). The authorities have sufficient technical systems and the related viewing and access rights, technical interfaces and statutory rights. The supervisory authorities will be provided with adequate mutual access and disclosure rights and rights to receive data gathered in radon measurements from various agents (MSAH).	Impact metrics on radon control in construction, housing, other indoor areas and workplace. Number, representativeness and usefulness of radon measurements recorded in the national radon database.
Raising radon risk awareness	HPA, Valvira, STUK, OSH, MSAH, building control supervision and the Association of Finnish Local and Regional Authorities engage in effective and influential communications and training for various target groups. If necessary, instructions, guides or other material will be prepared to support the achievement of the target.	Results of radon risk awareness surveys.

2.2 Changes in the living environment affecting radon-induced lung cancer

This section presents changes in society that may affect the prevalence of radon-induced lung cancer.

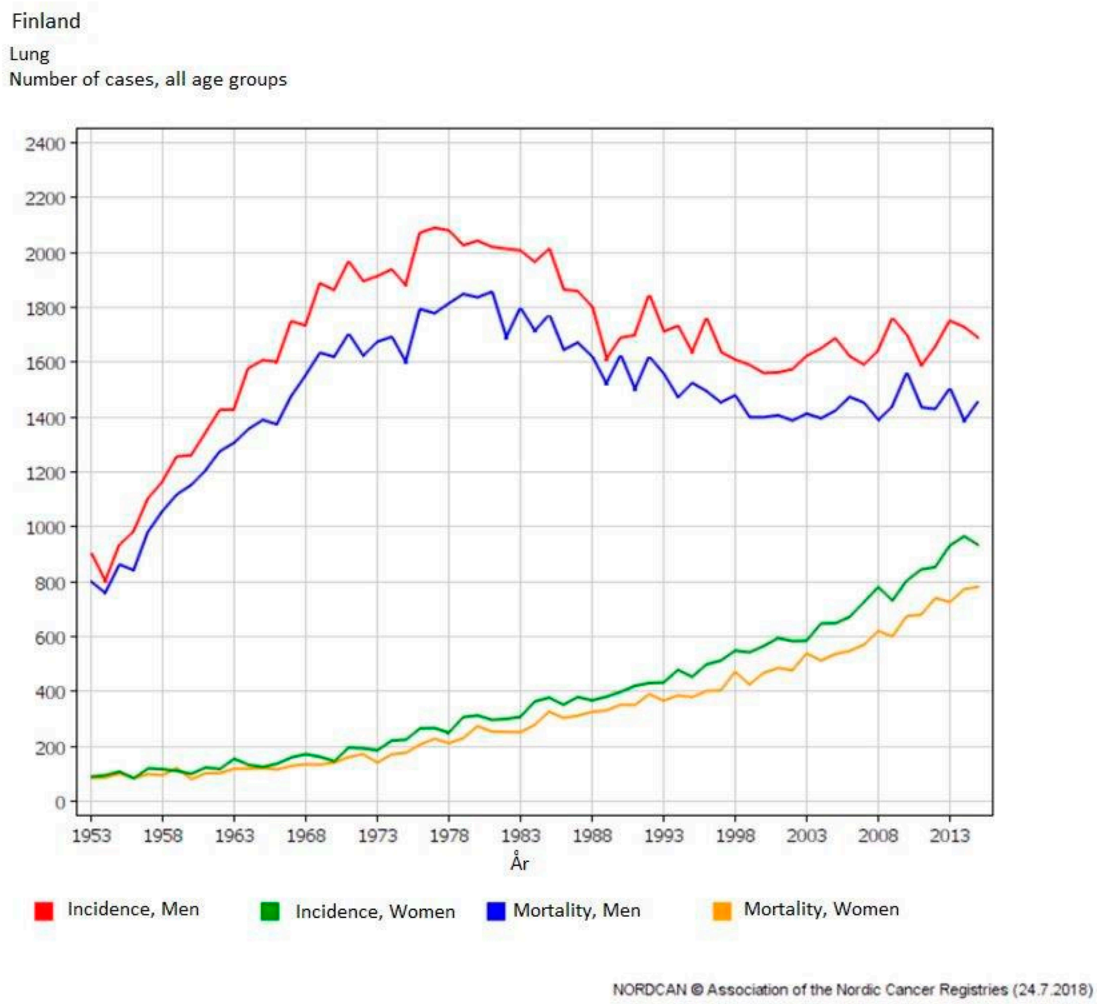
Smoking is becoming less common

In recent years, smoking has been in a continuous decline in Finland. Anti-smoking campaigns, such as Tobacco-Free Finland 2030, changes to the Tobacco Act and the enforcement of the Tobacco Act as well as changes to overall anti-smoking attitudes reduce smoking in Finland, and therefor also contributing to a decline in the number of radon-related lung cancers. As smoking decreases in Finland, fewer lung cancers caused by radon will be diagnosed. The committee statement by the Parliament Environment Committee to the Radiation Act (YmVL 14/2018 vp–HE 28/2018 vp) drew attention to the combined effect of radon and smoking, and encourages continuing the guidance, advice and other measures to promote a non-smoking lifestyle.

The most important risk factor for lung cancer is smoking. Reducing smoking and the starting of smoking among the population is key to preventing lung cancer. Legislation on tobacco in Finland extensively covers the use and control of various tobacco products. The objective of the Tobacco Act (549/2016) is to end the use of tobacco products and other nicotine products by 2030. Smoking reduction is part of the basic tasks of health care, promotion of wellbeing and preventive substance abuse work as well as numerous organisations. The educational duties of the organisations involved in the anti-smoking efforts have been divided between the agents: for instance, cancer organisations are responsible for providing education aiming to prevent the starting of tobacco and nicotine use among children and young people, while the FILHA ry association (an expert organisation on tuberculosis and pulmonary diseases) provides health care professionals with training on the skills required in supporting tobacco users to quit smoking. The Finnish Institute for Health and Welfare and the Finnish Institute of Occupational Health are involved in the Tobacco-free Finland 2030 network of doctors and many third-sector associations. The aim of the network is to present proposals for measures that promote a non-smoking lifestyle to support decision-making.

The prevalence of smoking is reflected by cancer statistics: In recent years, the number of cases of lung cancer has remained unchanged among Finnish men, while the incidence and mortality related to lung cancer has increased among women (Figure 5).

Figure 5. Number of cases of lung cancer in Finland, 1953–2015. http://www-dep.iarc.fr/ NORDCAN/FI/frame.asp



The declining numbers of cases of lung cancer cannot be set as a target, as the main cause of lung cancer, smoking, affects incidence and mortality rates so significantly, and smoking reduction is carried out in other programmes. The prevalence of smoking also varies across Finland (Murto et al. 2017). Therefore, it is impossible to see the impact of reduced radon exposure on the incidence of lung cancer in cancer statistics at the regional or national level.

Healthy Premises 2028

On 3 May 2018, the Government adopted the Healthy Premises 2028 operational programme, "Towards comprehensive promotion of wellbeing and paying attention to users in public buildings". The aim of the project is to promote the health and wellbeing related to public premises. Sustainable construction and maintenance practices and the prevention and treatment of indoor air problems, such as radon, are strengthened in the Healthy Premises 2028 operational programme implemented in the period 2018–2028. https://tilatjaterveys.fi.

Urbanisation

As the number of residents in blocks of flats is constantly increasing, in the future, more and more people will live on the second or upper floors of blocks of flats, where radon concentrations are relatively small. This may result in a reduction of the average exposure of the population to radon. On the other hand, dense detached housing has also become more common. However, the average radon concentration to which people in Finland are exposed in homes does not change very quickly, as the housing stock is slow to change.

Climate change

The final overall impact of climate change is likely to be small, but no study in more detail has been carried out on the subject. In theory, global warming can affect indoor air radon concentrations. However, no studies have explored the issue in detail. A reduction in differences between indoor and outdoor temperatures may result in a slight decline in radon emitted to indoor spaces. The difference in temperature has the biggest impact on houses with a natural ventilation system. On the other hand, natural ventilation works less efficiently when the temperature difference decreases, and leading to an increase in the radon concentration. However, the top floors of blocks of flats are unaffected. In addition, the water content in the soil due to rains in winter and the overall increase in rainfall may increase radon concentrations.

Energy efficient buildings

The energy performance of buildings directive of the European Parliament and of the Council requires Member States to take national guidance measures to improve the energy performance of buildings. An EU directive that requires all new buildings to be nearly zero-energy buildings (NZEB) will enter into force in early 2021. The properties of low-energy and passive construction include increased thermal insulation, good airtightness of the building envelope and mechanical ventilation. Even tiny air leaks through the foundation and base floor of a building may affect radon concentrations, even in cases where they do not significantly impair the overall airtightness of the building.

The quality of indoor air, including radon, must also be taken into account in energy-efficient buildings. For example, the minimum requirement for the extent of outdoor air flow is laid down in Decree 1009/2017 and it also applies to nearly zero-energy buildings. The topic concerns new houses and, in particular, old houses subject to a renovation that meets the new energy regulations, as ensuring the airtightness of the base floor is highly relevant in this context.

3 Reference levels, statutes and developing enforcement

The implementation of radon safety is enforced in the administrative branches of the Ministry of Social Affairs and Health and the Ministry of the Environment. In the administrative branch of the Ministry of Social Affairs and Health, the Radiation and Nuclear Safety Authority, municipal health protection authorities and the occupational safety and health authorities of the Regional State Administrative Agencies participate in monitoring radon safety. In the administrative branch of the Ministry of the Environment, the responsibility for supervision lies with the municipality's building control authority. At the local level, municipalities are responsible for environmental and housing issues. The monitoring of radon safety is based on several different laws, in which the objective, object and means of regulation differ. (Appendix 2)

Statutes related to radon include:

Radiation Act (859/2018)

Government Decree on Ionising Radiation (1034/2018)

Ministry of Social Affairs and Health Decree on Ionising Radiation (1044/2018)

Radiation and Nuclear Safety Authority's regulation on practice that causes exposure to natural radiation (S/3/2019)

Decree of the Ministry of Social Affairs and Health on quality requirements and regulatory control for household water (1352/2015)

Decree of the Ministry of Social Affairs and Health on the quality standards and regulatory control of household water (Small Household Water Decree; 401/2001)

Land Use and Building Act (132/1999)

Decree of the Ministry of the Environment on Foundation Structures, 465/2014

Decree of the Ministry of the Environment on the Indoor Climate and Ventilation of New buildings (1009/2017)

3.1 Background of reference levels under the Radiation Act

Under the Radiation Act (859/2018), reference level refers to the value of the radiation dose, exposure or activity concentration which would not be appropriate to be allowed to exceed in an existing exposure situation. The definition corresponds to the definition of the concept of the reference level in the Directive (2013/59/

Euratom) for basic safety standards for protection against the dangers arising from radiation. Under the Radiation Act, the existing exposure situation means an exposure situation attributable to ionizing radiation which does not constitute an emergency exposure situation or radiation practices. Depending on the context, the reference level applies for example to occupational or population exposure and can be expressed as e.g. radon concentration in breathing air or as radon exposure. As a rule, the reference level is not a limit value that concentration or exposure should not exceed under any circumstances. For example, in the case of radon concentrations in individual dwellings, radon concentrations above the reference level may be permitted for justified reasons. On the other hand, in connection with employees' exposure to radon, exposure above the reference level obliges the employer to take measures to reduce and/or monitor radiation exposure.

The BSS Directive (2013 /59/Euratom) requires setting a reference level not exceeding 300 Bq/ m^3 for radon concentration at workplaces at the national level. The reference level may not be higher unless this is required by national circumstances. The Directive does not contain a corresponding possibility for derivation for dwellings; i.e. the reference level of radon concentration may not exceed 300 Bq/ m^3 in dwellings. Possible national circumstances on the basis of which the reference levels for the radon concentrations at workplaces should be higher than what the directive proposes in Finland could have been that:

- The average uranium content in Finland's soil and bedrock is 3 mg/kg, while the global average is approximately 2 mg/kg.
- Finnish construction method, especially ground supported floor slab, causes radon leakage from the soil in buildings.
- The cold climate causes negative pressure in housing, which increases the radon concentration in the indoor air of buildings.

Modern technology enables designing and constructing buildings in a way that ensures keeping radon concentrations of indoor air as low as possible. In addition, concentrations corresponding to the radon concentrations in indoor air measured in Finland are also found in many other countries (Figure 4). As a result, a decision was made in Finland to determine the reference level for radon concentration of 300 Bq/ m^3, and not higher, at workplaces.

3.2 New buildings

Section 21 of the Ministry of Social Affairs and Health Decree on Ionising Radiation (1044/2018) lays down that the reference level for indoor air radon concentration for the design and construction of a new building is **200 Bq/m^3**. The reference level fora new building is applied when assessing whether a building has been designed and constructed to be radon safe. Section 21 of the Decree of the Ministry of the Environment (1009/2017) requires that buildings must be designed in such a way as to avoid the transfer of radon to indoor air. Section 4 of the Decree of the Ministry of the Environment on Foundation Structures (465/2014) lays down that the radon risks at a construction site must be taken into account in the design and construction of a building.

According to Statistics Finland, around 74,900 single-family houses have been built in Finland in the period 2000-2018. The STUK radon database includes the radon measurement results of 6,040 single-family houses built during the period and measured within five years of the completion of the building. Based on this, we cannot estimate how many new single-family houses conduct measurements of radon concentrations in indoor air. This is due to the fact that only measurements carried out with a radon plastic detector provided by STUK are stored in the database, and the year of construction is often not given.

3.3 Dwellings and other premises used by people

Section 20 of the Ministry of Social Affairs and Health Decree on Ionising Radiation (1044/2018) lays down that the reference level for a dwelling or premises used by people is **300 Bq/m^3**. The radon concentration in a dwelling is determined as the annual average concentration of radon, which is measured or estimated based on measurements carried out over a continuous period of one year. The radon concentration of the other premises used by people is calculated or measured as the annual average of the radon concentration in the space during its use.

A large proportion of other premises used by people are also workplaces, in which case the exposure of customers may be much more limited compared to employees (e.g. libraries, shops). Under section 13 of the Health Protection Act, the activities subject to the reporting obligation mainly fall within the scope of systematic monitoring by the authorities. The municipal health protection authority requests these agents to provide a report on the radon concentration of indoor air when the responsibility for investigating the matter falls to the authority due to its location. For indoor areas other than those subject to systematic monitoring, the municipal health protection authority monitors the radon concentration of indoor air based on control requests submitted to it.

According to section 202 of the transitional provision of the Radiation Act, a dwelling or other premises used by people built prior to the Act's entry into force which is not a workplace and the radon concentration of which has been found, by measurements and prior to the Act's entry into force, to be between 300 and 400 Bq/ m^3 shall ensure compliance with the provided reference level no later than in the context of the next repair measure in which a reduction of the radon concentration is practical.

So far, the median annual average radon concentration of the dwellings recorded in the national radon database was 125 Bq/m^3. In the measurements carried out using the STUK radon plastic detectors, the radon concentration has been higher than 300 Bq/m^3 in less than 20% of dwellings. In Finland, it is estimated that there are approximately 100,000 dwellings with radon concentrations greater than 300 Bq/m^3 and around 40% of them have been found. Based on estimates, around half of the dwellings whose radon concentration exceeds the reference level are mitigated to be safe. The application of the reference level is likely to be realised when a dwelling is sold or leased.

According to an estimate by the Ministry of Social Affairs and Health, radon concentration exceeds 300 Bq/m^3 in at most 3% of other premises used by people. This would mean around 3,000 buildings.

Radon is not mentioned in the so-called Housing safety Decree (Decree of the Ministry of Social Affairs and Health on Health-related Conditions of Housing and Other Residential Buildings and Qualification Requirements for Third-party Experts 545/2015), as a decision was made to reflect and discuss on the reference levels for radon concentrations in indoor air in connection with the reform of the Radiation Act. Section 3 of the Decree states that a health hazard must be evaluated as an entity in a manner which, in the application of the action limit for an exposure agent, takes into account the probability, repeated nature and duration of exposure, possibilities to avoid exposure or to eliminate the hazard, and the conditions caused by the elimination and other similar factors.

Section 26 of the Health Protection Act (763/1994) defines the health requirements for dwellings and other premises used by people, including radiation. The provision of the Health Protection Act is not limited to radon or even ionizing radiation, but applies to all radiation harmful to health. However, this action plan expressly examines it from the perspective of radon exposure. The provision requires that radon released from the soil must not enter into dwellings or other premises used by people to the extent that it poses a risk to human health.

With regard to dwellings or other premises used by people, the obligation to limit and eliminate radon concentration is based on section 27 of the Health Protection Act and is bound to causing a health hazard. In the case of radon, the owner of the building is usually responsible for investigating and eliminating the potential hazard. However, if this is not accomplished, the municipal health protection authority may oblige the owner of the building or the person responsible for the harm to take the necessary measures to investigate, eliminate or limit the health hazard. If the health hazard is obvious and there is reason to suspect that it poses an immediate risk, the hazard cannot be eliminated, or if an order by the health protection authority to eliminate the hazard has not been complied with, and other measures under this Act are not considered sufficient, the health protection authority may prohibit or restrict the use of the dwelling or other premises used by people.

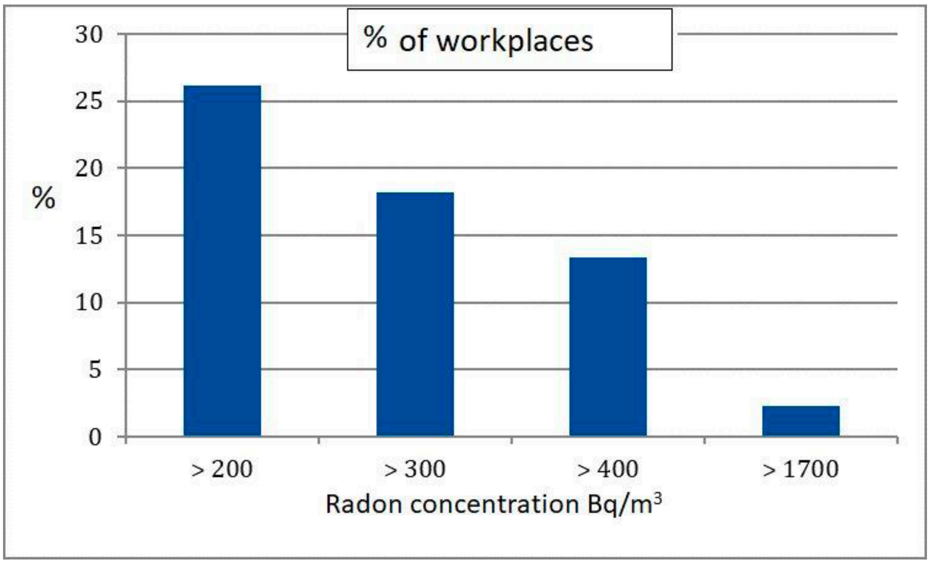
The Decision of the Ministry of Social Affairs and Health on maximum values for radon in indoor air 944/1992 (Finlex, in Finnish) has been repealed as a result of the reform of the Radiation Act.

3.4 Workplaces and employees

Section 19 of the Ministry of Social Affairs and Health Decree on Ionising Radiation provides that the reference level for **radon concentration** at a workplace is 300 Bq/m^3 in a working space where the working time spent by employees is greater than or equal to 600 hours per year. Radon concentration is calculated as the annual average radon concentration during working hours.

Based on the radon database, the radon concentration at around 18% of workplaces was higher than the reference level of 300 Bq/m^3 in at least one measurement point (Figure 6).

Figure 6. Distribution of radon concentrations in workplaces measured using the radon plastic detectors by all suppliers, 2015–2019.



The **reference level for the occupational exposure** to radon is **500,000 becquerel hours per cubic metre per year**. Exposure is calculated as the sum of all exposure accumulated during the year in all workspaces. The reference level for the occupational exposure to radon does not apply if an employee only works in a workspace where the radon concentration is lower than the reference level for radon concentration in indoor air at the workplace.

The reference level for radon laid down in section 19 of the Ministry of Social Affairs and Health Decree on Ionising Radiation is applied in situations where the radon concentration exceeds the reference level in some workspace or other premises used by employees.

In such cases, the radon concentration of the workspaces or other premises used by the employees and the time employees spend in them are included in the employees' total radon exposure. If the workspace or other premises used by the employees is located on a second floor or higher from the ground, there is no reason to measure radon concentration in the premises; instead, the radon concentration is assumed to be 40 Bq/m^3.

Safety licence and individual monitoring

Practices are subject to a safety licence if the occupational exposure arising from the radon concentration in workplace continues to exceed the reference level despite the measures taken to correct it (section 148 of the Radiation Act). Among other issues, this means individual monitoring of the dose of radiation employees are exposed to. The dose resulting from radon exposure is calculated in accordance with section 1.2 of Appendix 3 to the Government Decree on Ionizing Radiation. If the dose of radiation that employees are exposed to may exceed the dose limit of a worker (20 mSv/year), the employer must make arrangements for individual monitoring for the employees without undue delay (section 13 of the Government Decree on Ionizing Radiation).

In workplaces where radon exposure cannot be reduced to a level below the reference level (e.g. extensive tunnel networks where employees carry out maintenance tasks), individual monitoring is continued throughout the operations.

So far, the dose caused by radon to employees has been estimated on the basis of the radon concentration of the workspaces and the periods of time spent in these. The monitoring has covered 5–9 undertakings and 26–90 employees in recent years.

3.5 As low as reasonably achievable (ALARA) principle

Radiation exposure caused by radon should be kept as low as reasonably achievable (ALARA principle). In practice, the ALARA principle also means reducing radon concentrations below the reference level when possible. The World Health Organisation has recommended the reference level for indoor air radon concentration in dwellings of 100 Bq/m^3 (WHO 2009). Based on current research data, the shape of the dose response between radon and lung cancer is linear -non- threshold. Approximately one third of the lung cancers caused by radon in Finland result from low radon concentrations of less than 100 Bq/m^3. Reducing radon exposure to below 100 Bq/m^3 is a good target if it is reasonably possible. The property owner is usually responsible for taking measures if the aim is to optimise radon exposure below the reference level in dwellings and other premises used by people.

For dwellings and other premises used by people, the end result of the radon exposure scenario and radon mitigation must be examined by applying the ALARA principle. If the radon concentration is still higher than the reference level after mitigations, but the radon concentration has been significantly reduced and no reasonable additional mitigations can further reduce the concentration, the outcome can be considered acceptable. Case-by-case discretion is applied to these kinds of situations.

Example 1: At the first measurement, the radon concentration in the dwellings has exceeded 2,000 Bq/m^3 and the radon concentration has decreased by more than 85% as a result of the installation of the radon suction pit and improved sealing. Ventilation has been found to function sufficiently well. There are no more reasonable corrective measures left. In such a situation, the health protection authority can interpret the reference level more flexibly.

Example 2: A radon concentration exceeding the reference level is measured at a library's basement storage space to which customers have access. There are no desks and chairs in the storage space, so no library users spend long periods of time there and no one is significantly exposed to radon. In this case, the health protection authority can interpret the reference level more flexibly, while ensuring that the exposure of those using the space remains low (e.g. 50 h/y x 1000 Bq/m^3 = 50 000 Bq/m^3 h/y). However, STUK monitors the site to ensure that the annual radon exposure of employees does not exceed 500 000 Bq/m^3 h/y

3.6 Household water

The Ministry of Social Affairs and Health has issued decrees on the quality requirements and regulatory control for household water (1352/2015, hereinafter referred to as the *Household Water Decree*) and the Decree of the Ministry of Social Affairs and Health on the quality standards and regulatory control of household water (401/2001, hereinafter referred to as the *Small Household Water Decree*). The requirements laid down in a EU Directive (2013/51/Euratom) on the maximum levels of radioactive substances in household water are included in the Household Water Decree. The quality requirements for radioactivity are presented in Appendix 1, Table 3 of the Household Water Decree.

The municipal health protection authority monitors household water that is used or delivered to a water distribution area to be used as household water, amounting to at least 10 m^3 per day or serving the needs of at least 50 people. Under the Household Water Decree, water used as part of public or commercial activities or in food premises with their own wells or other water sources is also monitored.

The **maximum level of radon concentration in the quality requirement is 1,000 becquerels per litre** (Bq/l). If the concentration exceeds this level, corrective action is necessary for radiation safety reasons, always without any further assessments regardless of the purpose of water use. Corrective measures must be taken whenever the quality requirement is not met. The quality requirement of the Household Water Decree corresponds to the reference level referred to in the Radiation Act.

In the Household Water Decree, the **maximum level of the quality requirement** for radon is **300 Bq/l**. If the concentration is higher, risk assessment is used to determine whether it is necessary to take corrective measures. If the radon concentration exceeds 100 Bq/l at the site that should fulfil the requirements the user's faucet, a bottling site, a place where water is taken from a tank or a site at a food processing facility where water is used), the concentration must be measured from raw water or water leaving a water treatment plant. The municipal health protection authority may request a risk assessment from STUK.

According to the Small Household Water Decree (401/2001), the municipal health protection authority supervises those establishments supplying household water that supply less than 10 m^3 per day or for less than 50 persons. Under the Small Household Water Decree, the supervision may also apply to water in an operator's water abstraction plant, which is used as part of small-scale and low-risk public or commercial activities. In addition, under the Small Household Water Decree, water from an operator's water abstraction plant used in food processing facilities can be monitored if the activities are of a low scale and low risk. Wells or other water abstraction sites in shared or private use whose water is used by fewer than 50 persons are not under the supervision of the municipal health protection authority but are instead responsible for monitoring the quality of their household water independently. **The maximum radon concentration for private wells is 1,000 Bq/l**. In the quality recommendations of the Small Household Water Decree, the maximum concentration of radon is 300 Bq/l. If necessary, the municipal health protection authority will issue regulations to reduce radon concentration or an order to use another water source.

3.7 Construction products

STUK supervises compliance with the radioactivity of construction products in Finland. Construction products are controlled based on the gamma radiation they emit. The reference level for exposure to gamma radiation from construction products is 1 mSv/year.

Section 53 of the Government Decree on Ionizing Radiation specified the construction products for which an examination of the radiation exposure caused by natural radiation must be performed. The manufacturer, transferor or importer of the construction product is responsible for assessing the need to examine radioactivity, performing an examination and related measurements, and notifying the STUK of the results of the report. Section 24 of the Ministry of Social Affairs and Health Decree on Ionising Radiation lays down the reference levels for exposure to the population caused by construction products. Sections 12–13 of the STUK regulation provide for the investigation of the exposure of the population caused by a construction product and related notifying. The provisions concerning the investigation of radiation exposure caused by a construction product also take into account the requirements of the Construction Products Directive.

4 Measurement

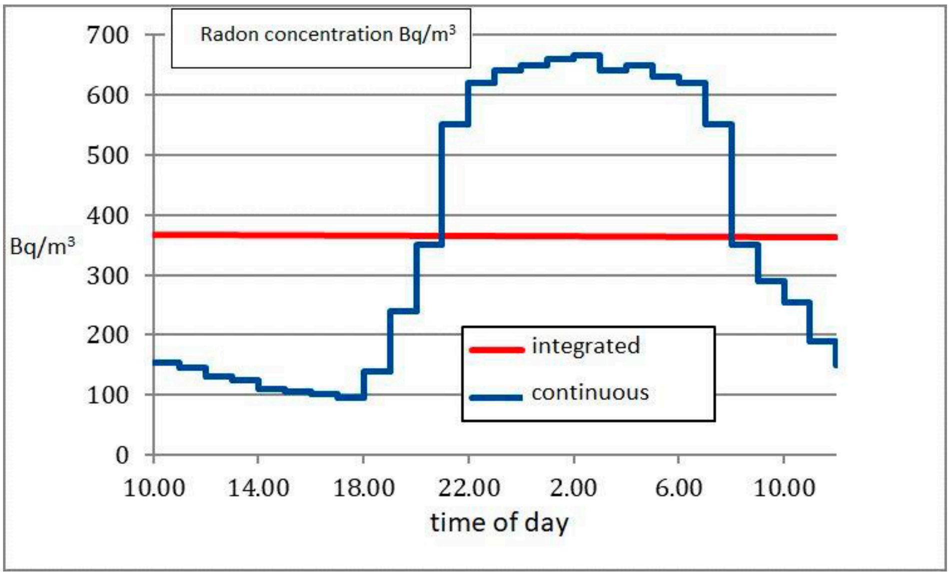
4.1 Methods and instruments

The equipment used for measuring the radon concentration in the air can be divided into integrated, continuous and spot measurement devices. An integrated measurement device records the number of detected radioactive decays cumulatively. When the instrument is no longer exposed to the radiation, the number of observations can be used to calculate the average radon concentration during the exposure period. Such instruments include alpha track detectors (the so-called radon plastic detector) and some low-cost semiconductor detectors.

Continuous radon measuring instruments measure and record radon concentrations over a short period ranging from minutes to a few hours. The measurement results stored on the device memory can be used to read radon concentrations during the periods or to calculate the average radon concentration over the time period examined (Figure 7).

The spot measurement instruments take an air sample and measure the concentration from this. In this case, the determined radon concentration represents the radon concentration prevailing at the time of sampling at the sampling site.

Figure 7. An example of comparing the results of continuous and integrated radon measurements in a space where ventilation is turned off outside working hours. The continuous measurement involves determining a radon concentration for each hour, while the integrated measurement performed using a radon plastic detector provides the average concentration for a longer period of time.



The different measurement approaches are applied for different purposes (Table 2). For example, the integrated measurement approach is ideal for estimating the radon concentration in a residential unit because it is inexpensive and the result indicates the average radon concentration in indoor air in the building over a long period of time. As the approach is inexpensive, it also makes sense to use it to perform the first measurement at workplaces, so that radon concentrations below the reference level can be excluded. If the integrated measurement reveals an average radon concentration exceeding the reference limit, continuous measurement should be carried out to determine variation in the radon concentration during the day. Especially in buildings with a time-controlled ventilation system, concentrations may be considerably higher at night time than during the day. On the other hand, sensitive continuous radon measurement instruments cannot be used for purposes such as when assessing whether it is necessary to increase ventilation in an underground tunnel before starting an installation project with a duration of a few weeks. Instantaneous measurement may be used in measuring the radon concentration in dusty and humid conditions in underground spaces where other radon measurement approaches cannot be used. The spot measurement of radon concentration involves taking an air sample whose radon concentration is subsequently measured in a laboratory.

Table 2. Comparison of radon measurement approaches.

Approach.	Benefits	Challenges
Integrated (radon plastic detector)	• Affordable • Enables measuring long-term average concentration	• Result describes the overall radon concentration, not concentration during work or when people spend time in the premises
Continuous	• Enables determining temporal variation in radon concentration per hour	• Price • Instruments must be calibrated regularly • Not suitable for carrying out long measurements because of price
Spot	• Enables determining radon concentration quickly • Not sensitive to environmental conditions	• The result only describes the radon concentration at the time of sampling
Small electronic detectors	• Less expensive than continuous indicators • Meter screen displays the average radon concentration	• Usually less sensitive compared to a continuous measurement instrument • No device-specific calibration, so there may be an error amounting to ±20 %

The radon concentration in the air in dwellings, other living areas and workplaces is determined by a measurement method approved by the Radiation and Nuclear Safety Authority for those looking to get an official measurement. However, other measurement approaches such as small electronic detectors can also be used to instantly check radon levels in connection with radon mitigation. A measurement lasting approximately 24 hours usually produces a sufficient number of pulses, and the device indicates the average radon concentration during this time on its display. Short-term measurement results must always be verified using a long-term measurement method approved by STUK. Short-term measurements are also useful in contexts such as work carried out in tunnels, as some devices show an estimate of the radon concentration in the space in a few hours, enabling improvements to ventilation if necessary. Some instruments also have an alarm feature that activates if the concentration exceeds the limit set by the user.

STUK has also approved a portable personal radon measuring device, which measures the radon exposure that employees are subject to. The measurement technology of this device is integrated. Compact semiconductor detectors could also be used as portable personal measuring devices.

4.2 Number of measurements

In dwellings smaller than 100 m^2, one radon measurement in the space where the residents spend most of their time is sufficient. In larger dwellings, one measurement is carried out for each 100 m^2 of residential space in the areas where the residents spend most time. In dwellings with two or more floors, radon measurements are carried out in each floor of residence. Basement washrooms and storage spaces do not need to be measured if people do not typically spend time there.

In ordinary workplaces, the location and number of measurement sites must be sufficient to ensure that the results provide a reliable estimate of the radon exposure of employees. It has been common for workplaces to measure radon concentrations at too few measurement sites, resulting in obtaining an unreliable picture of the radon exposure of employees. Chapter 5 of the STUK regulation (S/3/2019) contains detailed provisions on how to carry out radon measurements at workplaces and report their results.

4.3 Repeating measurements

Cases where a radon suction pit has broken without anyone noticing have come to STUK's attention. As a result, those using the premises have been exposed to the same levels of radon as before the radon mitigation efforts.

STUK recommends that indoor air radon measurements should be repeated in dwellings, other premises used by people and ordinary workplaces

- once every 10 years if the previous radon concentration has exceeded 100 Bq/m^3;
- once every 10 years if mitigation measures have succeeded in reducing
- the radon concentration below the reference level;
- once every 5 years if mitigation measures have succeeded in reducing
- the radon concentration below the reference level and the radon level
- exceeded 1 000 Bq/m^3 before the mitigation;
- as soon as possible after the building has been subject to
- significant construction or alteration work related to structures or ventilation (e.g. renewal of concrete slab, drains or ventilation).

The measurement of the radon concentration during working hours is repeated when significant changes are made to ventilation settings, which may have a significant impact on the pressure ratios and, consequently, the radon concentration during working hours.

Section 17 of the STUK regulation (S/3/2019) contains detailed provisions on the frequency of repeating radon measurements in underground workplaces.

4.4 Duration of radon measurement and measurement period

As radon concentrations vary from day to day and week to week and according to different seasons, radon concentration must be measured over a long period of time. The longer the measurement, the less random variations affect the measurement result.

The measurement of indoor air radon concentration must be continuous in dwellings and other premises used by people and ordinary workplaces and must have the duration of at least two months. The measurement must be carried out between the beginning of September and the end of May (measurement period from 1 September to 31 May).

Chapter 5 of STUK regulation (S/3/2019) contains provisions on the duration and measurement period of integrated and continuous radon measurements.

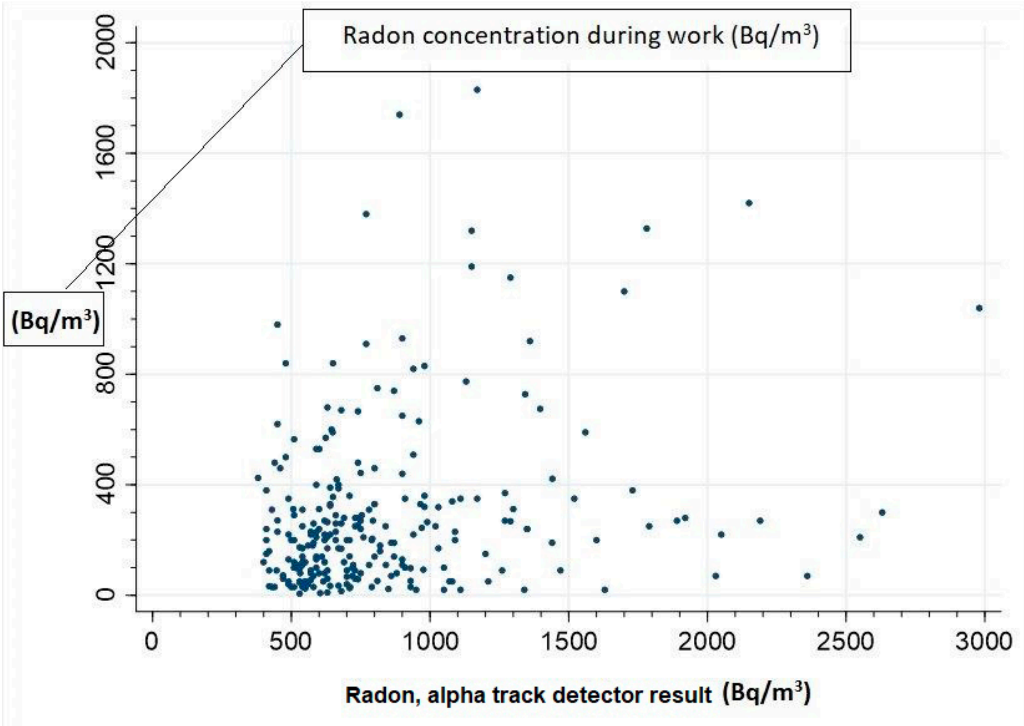
Based on both international recommendations (WHO 2009, ICRU 2012) and Finnish research data (Arvela et al. 2016), the duration of measurement should be extended to three months. This would significantly reduce the impact of random variation on the results. According to the analysis carried out by Turtiainen et al. (2018), the estimate of the annual average calculated based on a two-month measurement period (between September and May) is associated with uncertainty amounting to 30% expressed as a geometric coefficient of variation. If the duration of the measurement is three months, the coefficient of variation is 24%. Some European countries, such as the United Kingdom, Belgium and Ireland, have already introduced a three-month measurement period. According to a study conducted in England (Miles et al. 2012), a three-month measurement carried out in spring and autumn gives the most accurate estimate of the annual average without correction factors. The use of correction factors with winter and summer measurements increases the uncertainty of the annual average.

As a result of the adoption of the Radiation Act, the measurement period was extended in Finland at the end of 2018 from the previous measurement period, which covered the period between November and April. The new measurement period is the period between the beginning of September and the end of May, and the measurement must have the duration of at least two months. The decision to extend the measurement period is based on an analysis of the monthly measurement results of 329 homes (Turtiainen et al. 2018). According to the analysis, the geometric coefficient of variation of the correction factor associated with the assessment of the annual average is between 21% and 36%, when the measurement is carried out between the beginning of September and the end of May and has the duration of two months. If the two-month measurement took place in full or in part between June and August, the coefficients of variation were between 37% and 123%.

The radon concentration measured in winter is on average 18% higher than the annual average in the single-family houses where the average radon concentration exceeds 100 Bq/m^3 during the winter. (STUK A242). The winter concentration was estimated to be 12% higher than the annual average in single-family houses and 10% higher in blocks of flats. In individual dwellings, the winter/annual average concentration ratio varies, and in around 20% of measurements, the result of the winter measurement is lower than the annual average. A measurement carried out in the summer cannot be used to assess the annual average, as it involves the greatest uncertainties (Mäkeläinen et al. 2009, Arvela et al. 2016).

Scheduled mechanical ventilation creates an additional challenge in assessing the radon concentration in buildings not constantly used by people. If the result of a measurement carried out over a period spanning at least two months exceeds the reference level, it is possible that the average radon concentration during working hours or time spent in the premises is actually lower than the reference level because of the scheduled mechanical ventilation system. In this case, the radon concentration during work or time spent in the premises can be verified based on continuous radon measurement lasting at least seven days. The results of the measurement must show the exact average radon concentration of seven days and the average radon concentration during working hours or time spent in the premises during the same period. 79% of the radon measurements in the national radon database carried out during working hours were below 400 Bq/m^3, even though the results of the plastic detector were higher than this (Figure 8).

Figure 8. Radon concentration during working hours is usually lower than the levels indicated by radon plastic detector results when the workplace has a forced ventilation system. Source: National radon database (N=249).



It is difficult to verify exceeding the average annual level close to the reference level in practice. The radon concentration in different rooms of a building varies on average by 30%, while there is on average 30% variation between different years, and also around 30% uncertainty related to the average radon concentration within the year of measurement. In addition, there is around 10% uncertainty associated with the measurement itself. This results in a total uncertainty of approximately 50% (ICRU, 2012). For example, if the measurement result is 320 ± 35 Bq/m^3, the annual average can be estimated at 270±140 Bq/m^3. In principle, exceeding the limit can be only verified with < 10% accuracy with a very long, two-year measurement period. However, this is not very practical. A shorter measurement period results in an increase in random variation in the environment and an increase in false positive and negative observations.

4.5 Calculating annual average radon concentration

Section 18 of the STUK regulation (S/3/2019) issues provisions on the calculation of the annual average radon concentration at workplaces. Based on recent research findings (Turtiainen et al. 2018), it is better to calculate the annual average radon concentration by multiplying the measurement result by 0.9, which gives a slightly more conservative estimate than the factor previously used. Previously, the annual average has been estimated by dividing the result of the measurement made during the measurement period by 1.2.

If the result of the integrated measurement multiplied by 0.9 is less than the reference level laid down in section 19 of the Ministry of Social Affairs and Health Decree on Ionising Radiation, the annual average radon concentration is also considered to be less than the reference level.

When assessing the annual average, it is important to remember that the correction factor varies considerably between different structures. The confidence interval for the correction factor (90%) is 0.6-1.5 for two-month and 0.7-1.3 for three-month measurements. The use of an average correction factor (0,9) has a significant impact on the uncertainty of the estimated annual average. Precise determination of the annual average requires carrying out measurements for a year.

This enables making recommendations for radon mitigation directly based on the measurement result. Based on sampling data (STUK A242), this practice works well, as most of the cases exceeding the reference level for the annual average can be identified on the basis of measurements made during the measurement period. The sample included conducting two consecutive radon measurements, each with the duration of six months.

4.6 Radon gas concentration in soil and exhalation measurements

In many countries, radon risk maps are based on measurements of radon gas in soil. Finland no longer carries out the measurements of radon gas in soil as STUK has a relatively good understanding of radon concentrations in single-family and terraced houses in different areas. Interpreting **soil radon gas measurements can also be very difficult** for the following reasons:

- Soil permeability is the most important parameter when assessing the migration of radon in soil. Soil is a heterogeneous medium; a single plot area may include moraine, rock and silt at different locations and depths. In order to obtain a comprehensive picture of soil permeability, several permeability measurements should be performed at different points and depths alongside the measurements of radon gas in soil.
- If soil radon gas measurements are made in unbuilt soil, the measurement results may be misleading. When local service infrastructure is introduced to a plot/area (including water pipelines, sewers, information and electrical cables, asphalted streets, pedestrian walkways, parks), the conditions for radon emissions may be significantly different than before building the infrastructure.
- The water content of soil and the height of groundwater, which may change during different seasons, affect the release of radon from soil granules and its movement in the soil.
- In permeable soil, weather-related phenomena have a significant effect on the radon gas concentration of the soil. As these include wind, humidity and temperature, the radon gas concentration measured in the same location may be different at various measurement times. Measurements should be performed during different seasons and over a long period.
- It is practically impossible to predict the radon concentration of a building later constructed at a site based on the radon concentration of the soil as this depends on a variety of factors (incl. the base floor structures of the building). There are no sufficiently reliable calculation models available. As a result, no safe reference level can be set for radon concentration in soil.
- The soil, gravel and crushed stones brought to the construction site are a source of radon in themselves. In addition, the capillary break layer of the base floor promotes the transfer of radon originating from the soil and filling layers to the indoor spaces of the building.

In other words, a reliable estimate of radon would require several field and laboratory measurements (including emanation measurements of filler gravel, i.e. measurements of how much radon is released from soil granules into the pore air in the soil). This would be much more expensive and laborious than preventing radon from entering indoor air at all times and every part of the building design and construction process. In the National Building Code of Finland, section 2.6 Site investigation and site inspection of the Design of foundations 2018 guideline included in the Strength and stability of structures chapter proposes that the radon risks at a construction site should be taken into account when performing a ground survey. The radon risk of the building foundation is always affected by both the soil originally found in the site and the backfill material and gravel used in the subsurface drainage system brought to the site. It is also noted that a thick layer of gravel filling can alone produce radon concentrations that exceed the maximum permitted levels for indoor areas.

4.7 Indoor air radon in water supply plants

Water supply plants should always first investigate how much radon is emitted from raw water to the air during water treatment. This can be done by simultaneously measuring radon concentration in raw and outgoing water. Subsequently, the amount of radon released from water treatment per day is calculated. The increase in radon concentration in the workspace can be roughly assessed as followed:

$$c\,(Rn\text{-}222) = \frac{\text{radon released per day}}{\text{Air volume of the workspace x (ventilation rate + 0,18 /d)}}$$

The ventilation rate refers to how many times per day the air volume of the workspace changes.

Example: The radon concentration of raw water is 45 Bq/l and the outgoing water is 35 Bq/l. The processed water amounts to 100 m^3, or 100,000 litres, per day. As a result, the amount of radon released per day is 1 million Bq [= (45 – 35 Bq/l) x 100 000 l/d]. The volume of the workspace is 100 m^3 and the ventilation rate 1 /h = 24 /d. This makes the estimate of the increase of radon concentration from the radon released from water:

$$\frac{1\,000\,000\ Bq/d}{100\ m^3\ \times (24\ /\mathrm{d} + 0{,}18/\mathrm{d})} \approx 400\ Bq/m^3$$

4.8 Measuring household water

The radioactivity of household waters is measured in a research laboratory that meets the requirements laid down in section 49a of the Health Protection Act. The Finnish Food Authority approves the laboratories whose results can be used under supervision. According to the Ministry of Social Affairs and Health's decision, STUK research laboratory does not require separate approval for measuring the radioactivity of household water, as the laboratory has been accredited and serves as a reference laboratory.

The National Supervisory Authority for Welfare and Health provides instructions to the health protection authorities in municipalities in the monitoring of radioactivity in accordance with the Household Water Decree https://www.valvira.fi/ymparistoterveys/terveydensuojelu/talousvesi/talousvesiasetuksen_soveltamisohje.

4.9 Measuring construction products

Currently, STUK is the only laboratory in Finland that carries out radioactivity measurements of construction products, which are used as the basis for estimating the level of radiation exposure caused to the population by construction products. These measurements determine thorium-232, radium-226, potassium-40 and caesium-137 activity concentrations.

In principle, it is possible that the activity of a construction product consists mainly of a Ra-226 isotope and the radiation exposure from gamma radiation falls slightly below the reference level. In this case, there is a risk that the construction product will produce a significant amount of radon in indoor air. However, such a situation is rare, as the Ra-226 / Th-232 activity ratio in natural aggregates is typically between 0.5 and 3. In addition, K-40 isotopes are always found in minerals. Therefore, a material whose radioactivity mostly consists of the isotope Ra-226 can only originate from a chemical process that involves separating different elements.

The highest Ra-226 concentration measured by STUK in natural rock material complying with the reference level is 120 Bq/kg. This is more than the exemption level of 100 Bq/kg ("Flag Book", 2000) recommended by the Nordic radiation protection authorities which is based on radon production rate of the material .

Construction product manufacturers may not be able to consider the radon exhalation properties of the material, as no reference levels have been set for it. As a result, testing laboratories should, in the statement section of a testing report, refer to the recommendation of the Nordic radiation protection authorities in cases where the radiation exposure due to gamma radiation is below the reference level, but the Ra-226 concentration is greater than 100 Bq/kg.

5 Mapping radon concentrations in indoor air

The purpose of the radon mapping carried out by STUK (http://www.stuk.fi/aiheet/radon/radon-suomessa/ suomen-radonkartat) has been to detect regions with high radon concentrations of indoor air and to investigate which building engineering solutions affect the radon concentrations in indoor air. The testing also enables the authorities to target regulatory control to high-risk areas. The development of radon concentrations over time in Finland must be monitored, as construction methods are constantly changing and new residential areas are planned and may have an impact on indoor air radon concentrations.

5.1 National radon database

Under section 19 of the Radiation Act, STUK maintains a register on the radon concentrations in dwellings, other premises used by people and workplaces. As a result of its radon measurement laboratory and the requirement for employers to notify of the radon concentrations at workplaces laid down in the Radiation Act, STUK has a constantly supplemented database of radon concentrations, comprehensive from an international perspective. The results of indoor air radon measurements carried out at STUK as well as the results of workplace radon measurements carried out by all radon measurement providers are collected in a national radon database, which is used in the targeting of supervision and the preparation of statistics, radon maps and other radon reports. However, the data in the radon database overestimate the radon concentrations in Finland as a whole, as dwellings are measured more in areas known to have high radon concentrations than in other parts of the country. Corrected ratios can be calculated taking into account regional measurement activity, in which case the average radon concentration of the measured dwellings is weighted by the total number of dwellings located in the area.

Radon measurements made by other agents than STUK are currently not comprehensively included in the national radon database. When it comes to measurements carried out at dwellings, none of the measurements carried out by other agents are included in the database. For workplaces, measurement results are available especially from workplaces which were found to have radon concentrations exceeding the previous level indicating a need for taking measures of 400 Bq/m^3. Based on the ST 12.1 guidelines, radon concentrations below this level did not have to be reported to STUK. As a result of the new radiation legislation, all workplaces must report all of their radon measurement results to STUK (section 146 of the Radiation Act).

In its statement on the Government proposal on the Radiation Act, the Parliament's Environment Committee encouraged compiling information on measurement results in order to increase the information available on radon concentrations and its usability. To promote radon testing, it would be valuable to utilise results of radon measurements performed by private individuals. For example, in the United Kingdom, acceptance of radon measurements by different operators is conditional on the measuring company delivering all measurement results to the national authority once a year. There is no similar practice in Finland.

The national radon database currently contains approximately 249,000 measurement results for radon concentrations from about 161,000 dwellings and 55,000 measurement results from about 7,000 workplaces. When taking into account measurements made by other parties performing measurements, it can be estimated that radon concentrations in Finland have been measured in more than 10% of dwellings and at about 10% of workplaces.

5.2 Sample surveys

Sample surveys provide a more representative understanding of the country's radon concentration situation compared to directly using a radon database. This is because more radon measurements are carried out in areas known to have a high radon concentration. As a consequence, the results of the radon database are unrepresentative and the average concentrations calculated are higher than the prevailing concentrations throughout the country. Meanwhile, the sampling shows only the situation of the year of measurement. Because radon concentrations vary even in the same space during different years, this may reduce the representativeness of the results obtained from the sampling.

Representative population sample surveys were conducted in Finland in 1991 and 2006 (Mäkeläinen et al. 2009). Special sampling was also carried out in 1996 (Eastern Uusimaa) and in 2009 and 2016 (new single-family houses).

The RATVA study (Radon during working hours and leisure time) was carried out between 2000 and 2001. In this context, radon measurements were carried out not only at home, but also at workplaces and using portable radon plastic detectors. The study also involved investigating how much time Finns spend in different kinds of indoor areas. The project included sending 171 people a radon plastic detector, which they kept at their workplace for at least two months (Mäkeläinen et al. 2005).

A sample study of new buildings (Kojo et al. 2016) examined the indoor radon concentrations of new single-family houses in Finland (building permit granted in 2013) and the prevalence of radon prevention measures. In 5.6% of the measurements, radon concentrations exceeded the reference level for new dwellings of 200 Bq/m^3. The impact of both radon prevention and tighter energy regulations on indoor air radon concentrations was also examined. As a result of increasing airtightness of buildings, radon concentrations also arose in single-family houses where radon prevention measures had not been taken.

5.3 Assessment of radon exposure in Finland's population

According to a sample study (Mäkeläinen et al. 2009), the average radon concentration in dwellings was 96 Bq/m^3 and median 56 Bq/m^3, and the average radon concentration to which a Finnish person is exposed at home was approximately 94 Bq/m^3. The weighted annual average of the measurements recorded in the national radon database (between 1980 and 2019) is 102 Bq/m^3 and the median 125 Bq/m^3. The average radon concentration to which Finns are exposed at home was estimated to be 94 Bq/m^3 in a sample study carried out in 2006 and 111 Bq/m^3 based on the results recorded in the radon database in 2019. (Table 3)

Table 3. Key figures of the national radon database and the national sample conducted in 2006 (Mäkeläinen et al. 2009) on indoor radon in single-family dwellings, population exposure and radon concentrations.

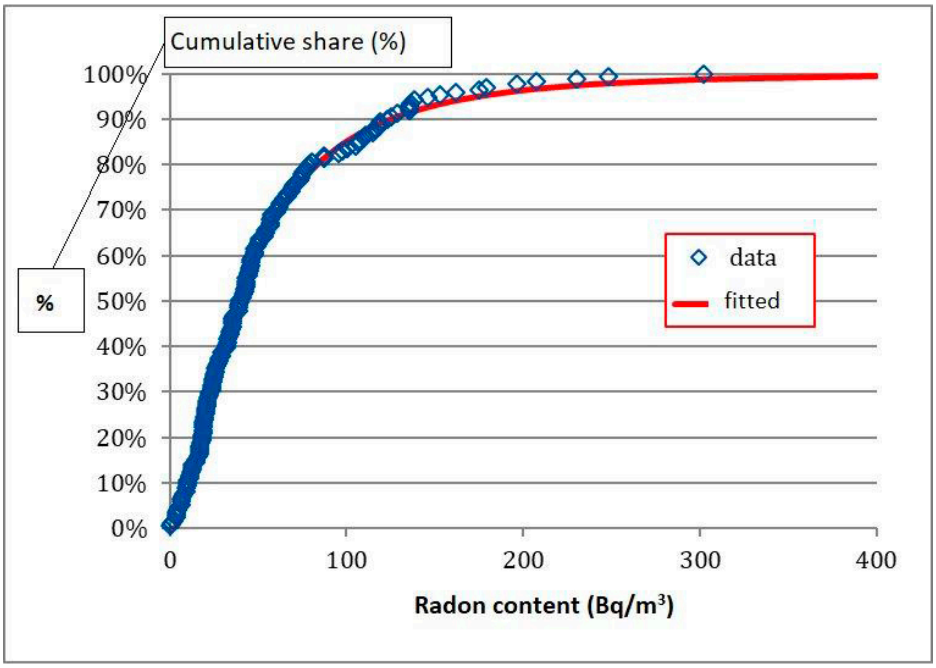
	Radon database 2019	Sample 2006
Radon concentration in all dwellings, average	102 Bq/m^3 (*)	96 Bq/m^3
Radon concentration in all dwellings, median	125 Bq/m^3	56 Bq/m^3
Average radon concentration that Finns are exposed to at home[1]	111 Bq/m^3 (*)	94 Bq/m^3

1 It is estimated that on average, 2.4 people live in single-family houses and 1.6 people live in blocks of flats.

* weighted value taking into account housing density to correct distortion caused by variation in regional measurement activity in different regions of Finland. The average radon concentration of the dwellings measured in each postal code is weighted by the total number of dwellings in the postal code area.

The concentrations measured in the RATVA project (Radon during working hours and leisure time) were fairly well in line with the log-normal distribution, so based on the study, it can be roughly estimated that approximately 1.3 % of employees are exposed to concentrations higher than 300 Bq/m^3 (Figure 9). As the number of employed people was 2,555,000 in Finland in May 2018 (error margin ± 33,000) (Statistics Finland 2018b), based on the RATVA data, it can be estimated that **approximately 30,000 employees are exposed to radon concentrations exceeding 300 Bq/m^3 in their work.**

Figure 9. Cumulative distribution of radon concentrations of workplaces measured in the RATVA project. Based on the fitted log-normal distribution, approximately 1.3% of employees are exposed to radon concentrations above 300 Bq/m^3.



5.4 Other databases

At present, different authorities do not have the possibility to make direct use of one another's data bases that contain data related to radon safety. In the near future, the aim is to promote the access of other authorities to the data of the national radon database.

6 Identifying high radon sites and areas

6.1 Dwellings

In all parts of Finland, property owners and holders and anyone undertaking a construction project must make sure that the radon concentration of indoor air is as low as possible taking into account the conditions. This can only be verified by radon measurement. Provisions on the supervision and mitigation of health damage caused by radiation in dwellings and other indoor spaces are also laid down in the Health Protection Act (763 / 1994).

The communications about radon targeted at dwellings should not use the actual regional radon risk division as radon concentrations can exceed reference levels everywhere in Finland. Nevertheless, there is considerable regional variation. The unofficial definition of "high-radon counties", previously used when referring to radon found in housing, should no longer be used, as the regional differences in radon concentrations have disappeared, at least in new buildings.

The Health Protection Act does not directly require performing radon measurements in dwellings. However, the indoor air conditions in dwellings must be such that they do not pose health risks to residents. Despite this, radon measurements are recommended in certain situations. For instance, it is a good practice to present radon measurement results in connection with selling real property. This ensures that the buyer is aware of the radon concentration in the building, while also avoiding any subsequent disputes. It is recommended that housing companies measure all apartments on the lowest floor to ensure equal access to healthy indoor air for all shareholders. Those renting out their property should measure the radon concentration in the dwellings before renting it out and informing potential tenants about the results. However, there is no need to performs measurements in the residential units on the second and upper floors of blocks of flats.

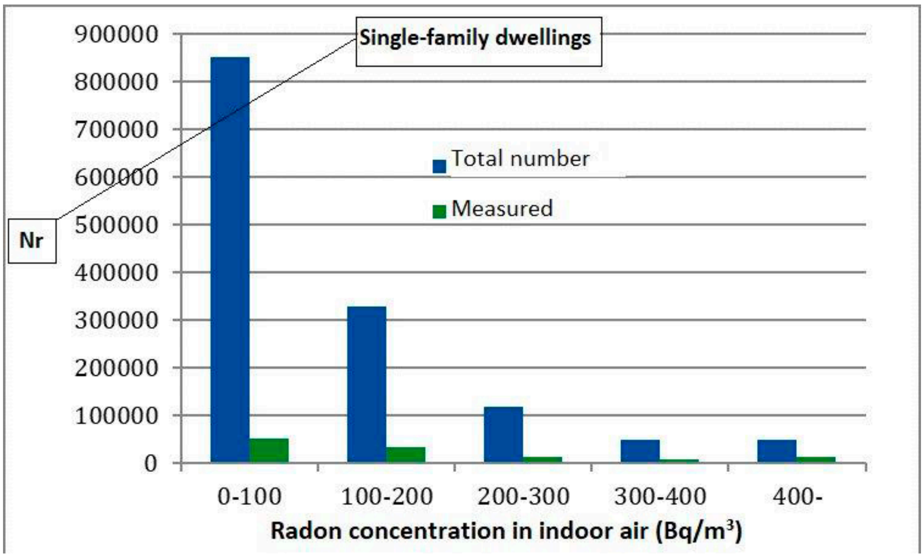
With regard to dwellings, the obligation to limit and eliminate radon concentration is based on section 27 of the Health Protection Act and is bound to causing a health hazard. As a rule, the owner of the building is responsible for investigating and eliminating the potential hazard. If the owner fails to take any action, the health protection authority may oblige the person responsible for the harm to take the necessary measures to investigate, remove or limit the health hazard and the factors leading to it. In the context of radon, the health protection authority may require the measurement of radon concentration in situations where the authority has reasonable doubt that the radon concentration in the dwellings may exceed the reference level (e.g. the dwelling is located in an area where high radon rates have been measured, the soil is very air-permeable (such as gravel or sand) and the dwelling is located on the lowest floor or partly below the ground). In practice, such

cases become evident in connection with the inspections of dwellings when a resident suspects that the dwelling is causing a health hazard and initiates the matter with the health protection authority. The authority usually primarily aims to investigate suspected health hazards related to radon by providing guidance and instructions. If, based on guidance and an overall assessment, the authority considers that the radon concentration in the dwelling will probably pose a health risk and that no radon measurements have been performed, the authority may also use administrative coercive measures. It should also be noted that an examination of a dwelling against the resident's wishes can only be carried out if the authority has reasonable grounds to suspect serious health harm requiring immediate action (section 46 of the Health Protection Act). In practice, an inspection due to radon alone cannot be carried out against the resident's will, because radon only increases the risk of permanent illness as a result of exposure accumulated over several years. In these situations, the authorities must use means of supervision other than an inspection, such as guidance and advice.

According to the Design of foundations section of the Strength and stability of structures chapter of the National Building Code of Finland (Ministry of the Environment 2018), the impact of the structure and/or action on the indoor air radon concentration can be determined by measuring the radon concentration in the indoor air after the construction work or action is completed.

The majority of dwellings in Finland (estimated at just under 90%) have not yet been measured (Figure 10). STUK does not have information on the results of radon measurements carried out by other providers of radon measurements for dwellings.

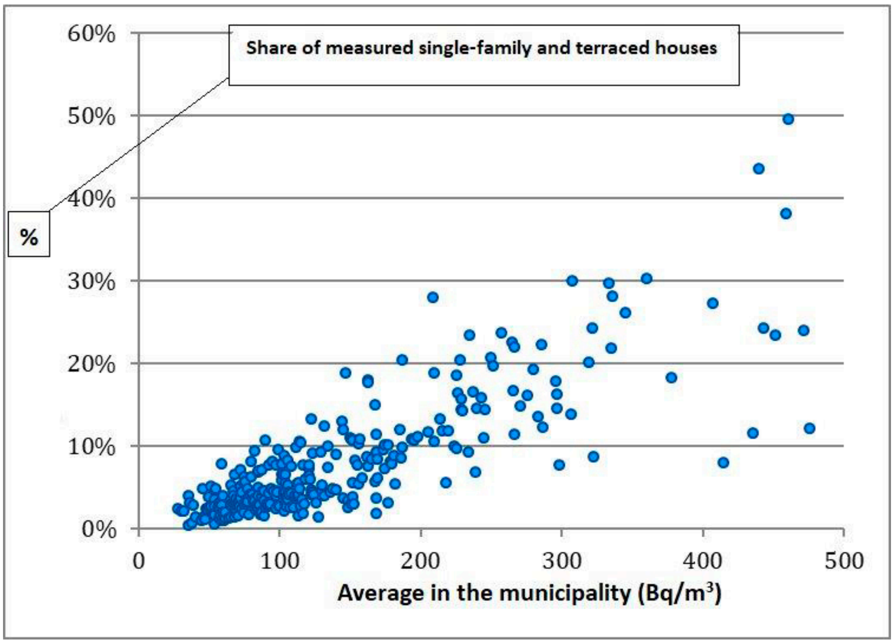
Figure 10. An estimate of the number of single-family dwellings (Total number) and radon concentrations in indoor air and the concentrations found in STUK measurements (Measured).



STUK laboratory provides radon measurements for dwellings as a service, and the smallest statistical unit of radon concentration is data per postal code (http://www.stuk.fi/aiheet/radon/radon-suomessa/pientaloasuntojen-radonpitoisuudet-suomen-kunnissa). These statistics can be easily used by municipalities in building control and environmental health care. The radon database can be used for purposes such as assessing which municipalities must improve the efficiency of their radon testing activities. At best, measurements have been performed in 50% of the municipality's single-family houses and terraced houses. (Figure 11)

However, information on regional radon concentrations may reduce the measurement activity of households. If only few measurements performed in the region exceed the reference level, people may interpret this to mean that there is no radon in the area and no reason to measure radon concentrations.

Figure 11. The share of tested single-family and terraced houses in municipalities based on the average levels of radon in municipalities. Radon concentrations are high in the area within the red oval, but the number of measurements in the area is relatively low. On the other hand, these municipal averages of radon concentrations generally include greater uncertainty due to the small number of measurements.



6.2 Other premises used by people

In accordance with section 156 of the Radiation Act, indoor radon concentration must be investigated in any other premises used by people as referred to in chapter 7 of the Health Protection Act, insofar as the spaces are located[2]:

1. in areas required to perform measurements defined by the Radiation and Nuclear Safety Authority (Figure 12);
2. on an esker or other gravel or sandy soil with good air permeability;
3. wholly or partly underground.

2 The same areas as for workplaces, of which more information is provided in the following section

The division of responsibilities concerning the investigation obligation complies with the provisions of section 27 (2) of the Health Protection Act concerning investigating, eliminating and restricting a health hazard.

However, the investigation need not be carried out if the space is located on the second or upper floor of the building seen from the ground level, or if the floor and walls of the building are not in contact with the ground and the good ventilation of the space in between is apparent.

In other premises typically used by people for long periods of time, such as day-care centres, schools and residential facilities, it is particularly important to investigate radon exposure because those exposed cannot personally influence the extent of radon exposure in the space. There is particularly need to limit the exposure of children as the radiation dose is accumulated throughout one's lifetime and as it is generally known that children are more vulnerable to the harmful effects of radiation.

6.3 Workplaces

In the efforts to protect the population against radiation, the aim is to target regulatory control to sites where it is most likely that effective results are obtained, meaning that radon exposure is most effectively reduced (graded approach).

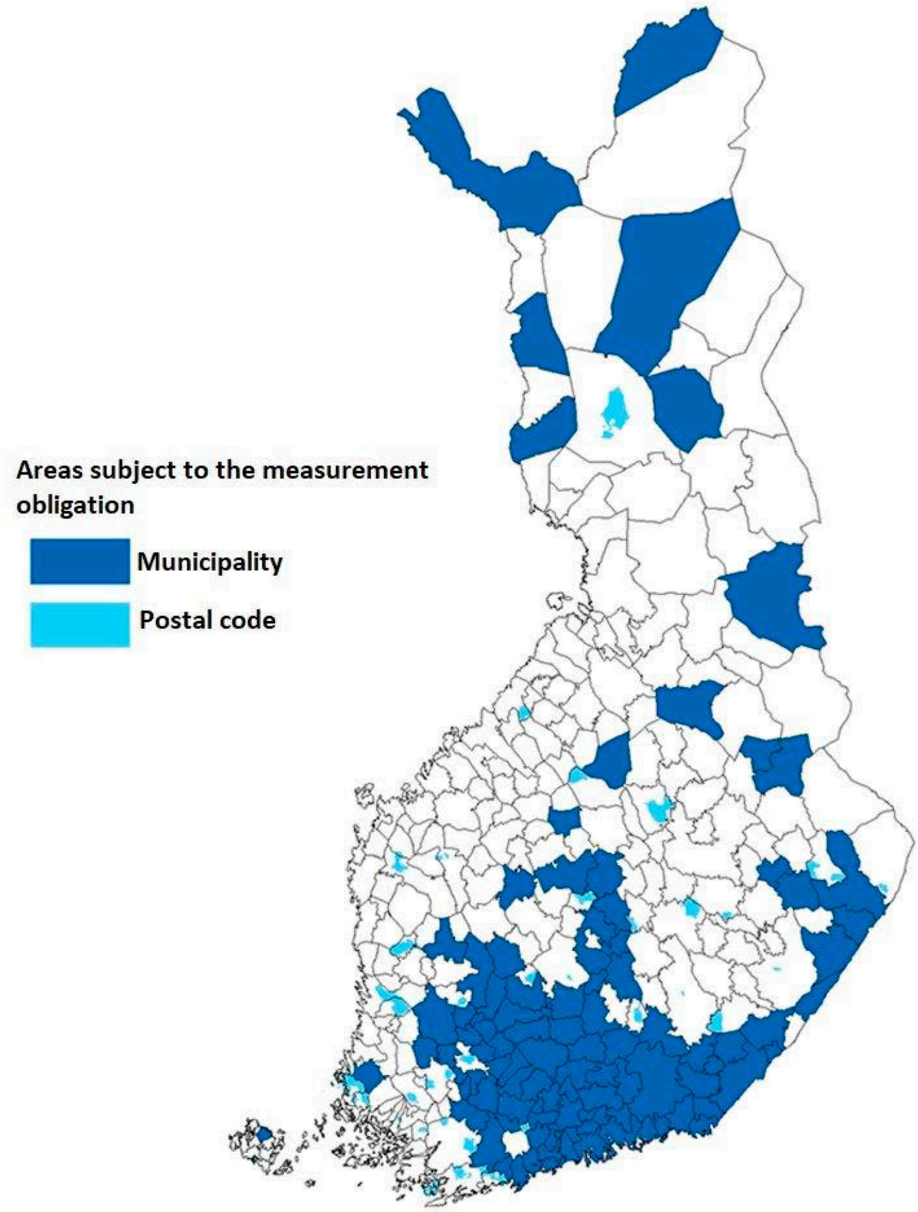
Under section 155 of the Radiation Act, an employer shall investigate the radon concentration in a workspace or other place of work if the facilities are located:

1. in areas defined by the Radiation and Nuclear Safety Authority in which more than a tenth of representative results of radon measurements exceed the reference level for radon concentrations in workplaces (Figure 12);
2. on an esker or other gravel or sandy soil with good air permeability;
3. wholly or partly underground;
4. in an installation which distributes water the water of which does not derive solely from a body of surface water and has contact with indoor air.

However, the investigation need not be carried out if none of the workers work in the workspace for more than 20 hours in a year or located on the second or upper floor of the building seen from the ground level, or if the floor and walls of the building are not in contact with the ground and the good ventilation of the space in between is apparent.

The Radiation and Nuclear Safety Authority maintains a list of areas where radon measurements must be carried out at workplaces.

Figure 12. Municipalities and postal code areas where the radon measurements performed at workplaces and other premises used by people must be based on the radon database. In addition to these areas, measurements must be performed at workplaces and other living areas that have been built on air-permeable soil types or that are completely or partially below the ground level.



Conditions at workplaces vary a lot. For example, in high hall spaces, ventilation is adjusted based on to the number of people in the space, not its volume, which results in a low ventilation factor.

In addition, circulating air may be used to stabilise temperatures. In a high space, warm air also causes greater negative pressure at the floor level compared to standard height work premises. The above factors increase radon concentrations.

7 Reducing and preventing high radon levels

It is possible to affect radon exposure in advance by limiting the indoor radon concentration in a construction project (section 157 of the Radiation Act) or later by limiting the indoor radon concentration in a dwelling or other space with public access (section 158 of the Radiation Act) or at a workplace (section 147).

As a result of increased radon awareness, supervision, guidelines and improved building practices, the radon concentrations in the indoor air of new buildings have decreased in Finland in recent years. There is still reason to monitor and promote this positive development. Radon exposure can be further reduced in connection with the renewal of the building stock if radon risks are appropriately taken into account in the planning and construction of new buildings throughout Finland. This requires raising awareness of radon safe structural solutions among those undertaking a construction project, construction professionals and the authorities responsible for monitoring related to the health and safety of construction (building control).

7.1 Radon prevention in new buildings

Radon prevention in new buildings is generally cost-effective, and easier and cheaper than taking radon mitigation measures in older buildings. The building owner is usually responsible for paying for the radon mitigation measures. In accordance with section 157 of the Radiation Act, the party undertaking a construction project must ensure that the building is designed and constructed in such a way that the indoor radon concentration is as low as possible.

Radon concentrations in the indoor air of new buildings have been constantly decreasing. Pursuant to the ALARA principle, the objective of radon prevention in new construction is to minimise radon concentrations that can be achieved at reasonable costs. The radon prevention efforts in new construction have achieved very positive results (Arvela et al. 2010, Kojo et al. 2016). As the housing stock is renewed and if radon prevention work becomes more common, population exposure will decrease. On the other hand, the building stock is renewing slowly.

In municipal building supervision, radon safety is included in the municipalities' building orders. The instructions concerning the construction of foundations has been made to include a recommendation on performing a radon measurement. It might be necessary to make the radon measurement mandatory in similarly as has been done with air-tightness measurements, as radon safety cannot be ensured otherwise than by measuring the radon concentration.

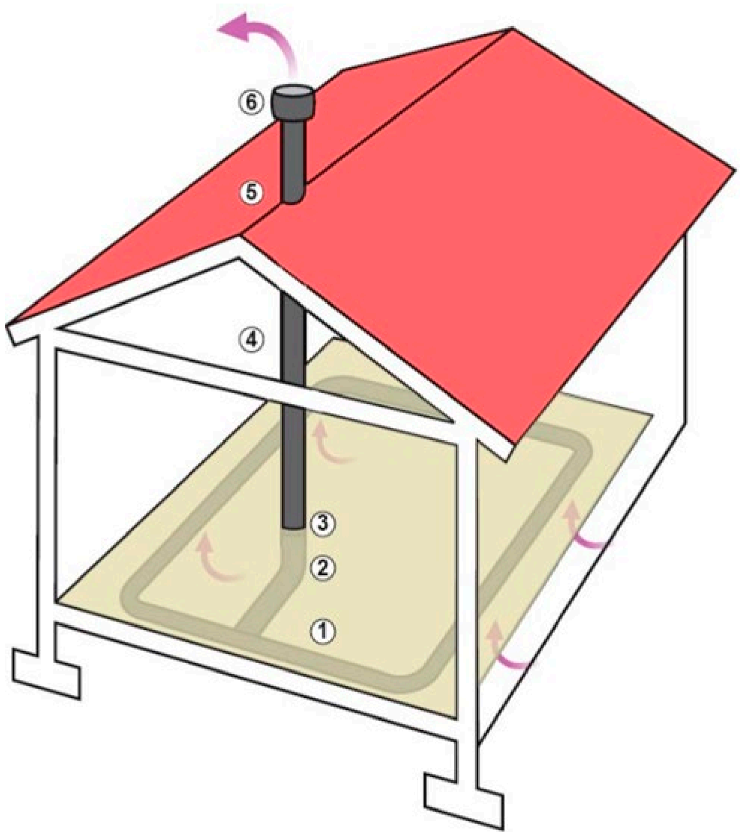
Under section 4 of the Decree of the Ministry of the Environment on Foundation Structures (465/2014) issued pursuant to the Land Use and Building Act, the radon risks of a construction site must be considered in the design and construction of a building. The Design of foundation section of the Strength and stability of structures chapter of the National Building Code of Finland (Ministry of the Environment 2018) has proposed that the adverse effects on indoor air quality from radon and other gases and impurities that are detrimental to health and comfort should be prevented with structures and/or actions that are applicable to the project under design. The guideline also indicates that the impact of the structure and/or action on the indoor air radon concentration can be determined by measuring the radon concentration in the indoor air after the construction work or action is completed.

Section 5 of the Decree of the Ministry of the Environment on the Indoor Climate and Ventilation of New Buildings (1009/2017) issues that indoor air may not contain amounts of physical factors hazardous to human health (incl. radon). Section 21 Decree of the Ministry of the Environment on Indoor Air and Ventilation of New Buildings (YMa 1009/2017) stipulates the following: "A specialised designer must design the external and outdoor air flows of the building in such a way that the structures do not cause long-term moisture stress that damages the structures due to overpressure or the transfer of impurities to indoor air due to negative pressure. In accordance with their tasks, the main designer, specialised designer and building designer must plan the airtightness of the building envelope and internal structures and stack effect management in such a way that the preconditions for proper ventilation can be ensured and the transfer of impurities in the structures, soil impurities and radon into indoor air is avoided and the transfer of moisture to the structures prevented."

Radon prevention in new buildings usually reduces radon concentrations by about 40%. Radon prevention is recommended for all new buildings throughout the country. Rakennustieto Oy publishes guidelines for radon prevention in new construction (Rt 103123, 2019). Radon concentration of indoor air is typically low in buildings with a crawl-space construction or a monolithic slab foundation and the sealing of pipe and wiring runs in the crawl space will usually suffice as a radon prevention measure. If ground-supported floor slab is laid in the buildings, radon prevention is carried out by installing radon piping (Figure 13), sealing the line between the foundation wall and the slab with rubber bitumen membrane and sealing any penetrations. If the radon concentration is greater than 200 Bq / m^3, the radon piping is activated connecting a roof fan to its exhaust duct.

This usually reduces the radon concentration by 70–90%. The costs of radon prevention in new buildings are approximately EUR 2,000 in single-family houses. Radon prevention practices for new construction are already well-established in Finland and they have clearly succeeded in reducing the radon concentrations in indoor air. Radon piping has been installed since the 1980s, and has not been shown to have adverse effects on the humidity conditions or structures of the base floor. By contrast, radon piping may have positive effects on the humidity conditions of the base floor, as the piping provides natural ventilation to the base floor. The drying effect is usually a positive thing. If the concrete slab dries too much, the role of diffusion in radon transport may increase (Kettunen 2019).

Figure 13. The radon piping consists of an underdrainage pipe (1), which is connected to a (2) plastic exhaust duct (4). The slab penetration (3) is carefully sealed. Exhaust duct is taken to the water roof (5) and its end is capped (6).



According to a 2009 sample survey of new houses (Arvela et al. 2010), radon prevention had been carried out in about half of single-family houses at the time of the survey. In counties with high radon concentrations, the prevention of radon was carried out in 92% of new single-family houses. In other parts of Finland, radon prevention measures had been taken in only 38% of new single-family houses. In the following sample concerning new houses in the period 2015–2016, radon prevention had been carried out in 98% of the new single-family houses in the municipalities with a high radon concentration and 61% of those elsewhere in Finland (Kojo et al. 2016).

It is important that the indoor radon concentration of new buildings is measured once the buildings are completed and used. Radon concentrations depend on many conditions. Therefore, the structures, external land fillings, ventilation and heating system must be fully completed before the radon measurement is performed. On the other hand, the duration of the radon measurement must be at least two months and it must be carried out during the radon measurement period. Because of these factors, the result of radon measurements is not always available at the time of the final review and it is not reasonable to require it. It is recommended that the radon measurement be carried out immediately during the official measurement period following the final inspection, which allows ensuring that the radon concentration in indoor air falls below the reference level as planned.

Low-energy construction can bring new challenges to radon prevention. Currently, the aim is to ensure a balance in air volumes, but malfunctions in ventilation systems and a lack of maintenance can lead to imbalances. Together, mechanical ventilation and good air-tightness may result in a significant spike in negative pressure in the building. This may lead to increased radon concentrations in indoor air. Even tiny air leaks in the base floor can increase radon concentrations in indoor air, also in cases where they do not significantly impair the overall airtightness of the building (Arvela et al. 2015). There were indications of this in a study, in which an increase in the airtightness of new buildings led to an increase in the radon concentration in those single-family houses where no radon prevention measures had been taken (Kojo et al. 2016). This observation highlights the importance of combating radon in airtight houses. In addition, attention must be paid to ventilation settings to ensure that the building is not excessively negatively pressurised.

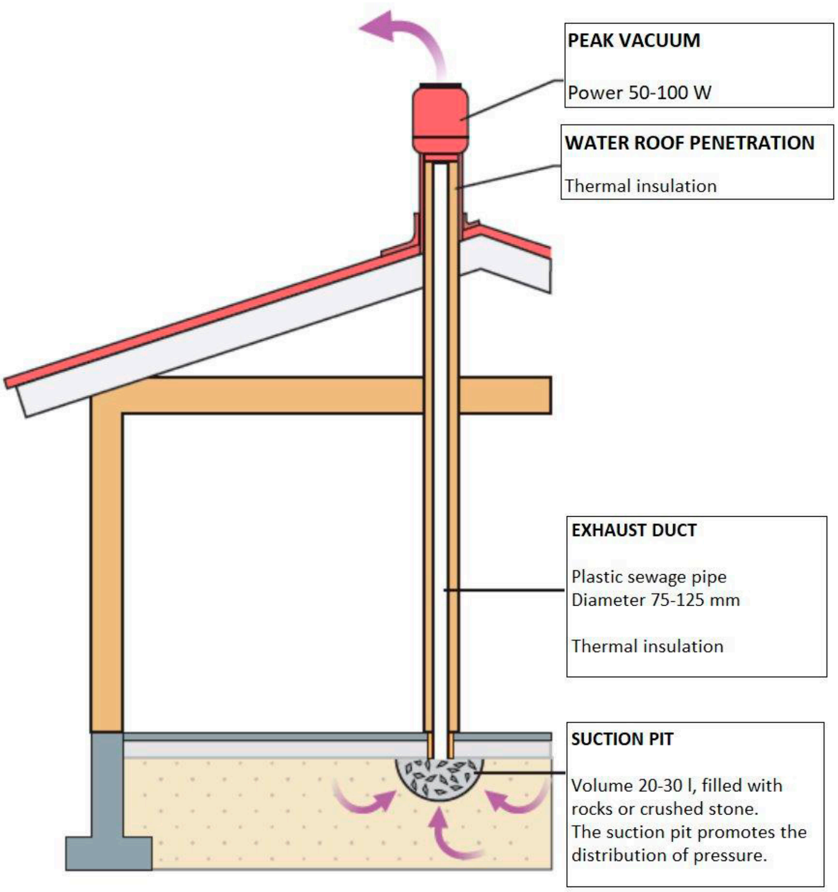
Taking into account the increase in the building stock caused by new construction, urbanisation, the removal of old buildings and the population projection, it can be estimated that it will nevertheless take at least decades for half of the housing stock to be renewed. Therefore, there will still be need for radon mitigation for a long time.

7.2 Radon mitigation

The key objective of radon mitigation is to prevent or reduce air leaks from the soil. Efficient radon mitigation measures include a radon suction pit and a radon well used to suck air soil and gravel filling from under the house. This reduces the flow of pore air with radon into the building (Figure 14). The radon well and suction pit typically reduce the radon concentration by 65–90%. Sealing the leakage point in the base floor and improving ventilation rarely reduce the radon concentration in indoor air by more than 50%. (Arvela et al. 2012). The first radon mitigation measures were carried out in Finland in the early 1980s. No building permit is usually required for radon mitigation.

The STUK indoor radon mitigation guide (Arvela et al. 2012) is available for downloading at the STUK website www.stuk.fi/radonkorjausopas. STUK has been organising radon mitigation training around Finland and webinars on the topic (https://www.stuk.fi/aiheet/radon/radonkorjaukset/ radonkorjauskoulutuksen-materiaalit).

Figure 14. Radon suction pit sucks air from under the floor, which effectively reduces the radon concentration of indoor air.



In addition to radon, a well-operating radon suction pit removes moisture from the gravel filling layers under the building and prevents other harmful gaseous substances from entering indoor areas.

7.2.1 Dwellings

Based on estimates, radon mitigation measures had been taken in around 6,000 single-family houses in Finland by the end of 2015. This amounts to 40% of single-family houses in which radon concentrations were measured and 12% of the single-family houses in which radon concentration was estimated to exceed 400 Bq/m^3 (previous level indicating a need for taking measures).

However, not all radon mitigation measures carried out in dwellings have been recorded in the database. According to STUK surveys, about half of the dwellings whose radon levels were measured to exceed the level indicating a need for mitigation have been mitigated to be radon safe. A 2011 survey indicated that the most common reason for neglecting radon mitigation in dwellings was the price of the mitigation measures. The average costs per household were EUR 2,300. Some had not been able to find sufficient instructions or companies providing radon mitigation work. Only 9% did not consider mitigation as important. Table 4

Table 4. Causes that prevent or hinder radon mitigation. The survey focused on houses with radon concentrations higher than 400 Bq/m^3 in the radon campaigns of 2008 and 2009. N = number of responses.

	No measures taken (N=451)	Mitigation measures completed (other than radon piping activation, N =354)	Radon piping activated (N=120)
Price	53%	35%	23%
Not enough instructions	19%	10%	8%
Lack of mitigation attempts	12%	11%	3%
Not considered necessary	9%	5%	4%
Other	40%	18%	12%
None selected	11%	44%	63%

As a rule, the owner of the building is responsible for the costs of radon mitigation. If efforts were made to find and mitigation all dwellings with radon concentration above 300 Bq/m^3, the estimated total price would be just under EUR 300 million. If the radon mitigation efforts were divided over a 20-year period, the annual costs would be EUR 14 million, which would increase all annual property mitigation costs by only 0.2%. Finland annually spends EUR 6 million to all mitigation measures of real property, and the total value of all real property and plots in Finland amounts to EUR 775 billion (http://www.stat.fi/til/rak.html).

7.2.2 Other premises used by people, public premises

The central government building stock covers around 10,000 buildings. However, no separate survey of the need for radon mitigation in the central government building stock has been completed. Based on radon measurements carried out at other workplaces,

it can be estimated that radon mitigation is required in approximately 10% of the building stock. According to estimates, there are around 3,000 public spaces with radon concentrations exceeding the reference level. As most of these premises also have other mitigation needs, attention should also be paid to radon in connection with renovating them. The radon concentration of indoor air can be reduced in several ways, depending on how much the concentration should be reduced and on the structural and building engineering solutions of the building. Typical methods of reducing radon concentration include measures related to enhancing and adjusting ventilation, sealing structures, and radon suction pits and radon wells. Ventilation control and enhancement can be estimated to cost approximately EUR 2,000 per building on average, and the improved air sealing to reduce radon concentration in public buildings can be estimated to cost approximately EUR 20,000 per building on average. The cost of a radon suction pit and well can be estimated to be approximately EUR 20,000 per building. Public buildings often need several radon suction pits and wells. In addition, mitigations to public buildings usually include planning and measurement costs as well as possible building permit costs. At least in large public buildings, it would be a good idea to require a building permit or action permit to ensure that mitigations are carried out correctly and that no other indoor air problems are caused. At a 300 Bq/m^3 reference level, the total mitigation costs can be estimate to be approximately EUR 20-35 million. Table 5 provides an estimate of the costs of radon mitigation in public premises, typically larger buildings than the average workplace.

Table 5. Estimate of the costs of radon mitigation for public buildings in Finland.

Measure	price/measure (€)	Reference level 300 Bq/m³	
		N	total price (€)
Measurement during working hours	2,000	1,200	2,000,000
Enhancing and adjusting ventilation	2,000	600	1,000,000
Sealing	10,000	600	6,000,000
Radon suction pit or well	20,000	600	12,000,000
Planning	3,500	1,200	4,000,000
Total		**3,000**	**25,000,000**

7.2.3 Workplaces

If the annual average radon concentration during work exceeds the reference level, the workplace must reduce the radon exposure of employees. The alternatives available for this usually include radon mitigation and also adjusting ventilation or limiting the use of premises. Radon mitigation at workplaces can be carried out using the same basic approaches as those used with dwellings, i.e. a radon suction pit, radon well, enhancing and adjusting ventilation, and improving the sealing of floor structures and penetrations.

The cost of mitigations varies greatly depending on the size and structure of the building (Table 6). The estimate is based on the number of employees assessed to be exposed to radon concentrations above 300 Bq/m³ (1.3% of employees) and the average number of employees in companies.

Table 6. Estimate of the costs of radon mitigation for workplaces in Finland. The number of workplaces is based on the number of employees working at radon concentrations above the reference level of 300 Bq/m^3.

Measure	Price / measure (€)	Workplaces with radon concentrations above the reference level	Price of total costs of radon mitigation (€)
Measurement of radon concentration during working hours	1,500	1,200	1,800,000
Enhancing and adjusting ventilation	500	600	300,000
Sealing	5,000	600	3,000,000
Radon suction pit or well	10,000	600	6,000,000
Total		**3,000**	**11,000,000**

7.3 Radon emitted from construction products to indoor air

The construction products referred to in section 153 of the Radiation Act which cause radiation exposure is greater than the reference level due to natural radiation include at least:

1. building frame structures produced of mineral-based raw materials;
2. construction products, in which the main raw material is crushed rock, gravel or sand containing granite or other granitoids, such as granodiorite, tonalite or gneiss;
3. construction products whose raw materials include intermediate products or by-products or waste originating from industries using ash or mineral-based natural raw materials.

Some construction products may contain enough radium-226 isotope to produce significant radon concentration in indoor air. In accordance with section 153 of the Radiation Act, anyone who manufactures, imports or transfers a construction product must investigate the radiation exposure caused by the product. Radioactive substances in construction products must be investigated if the combined exposure resulting from the radioactivity of the construction products in the product's intended purpose of use can exceed the reference level. Currently, the STUK laboratory is the only operator in Finland performing measurements of the radioactivity of construction products. The laboratory submits the results to the agents monitoring the radioactivity of construction products in accordance with the terms of service of the measurement service. If necessary, STUK may oblige the party responsible for the activities to use the material only for filling the land, but not for building a house.

7.4 Radon emitted from household water to indoor air

In Finland, bore wells can be a significant source of indoor radon. In an estimated 6,000 households, household water contains more than 1,000 Bq/l of radon, which causes an average increase of 40 Bq/m^3 of radon concentration in indoor air (Turtiainen and Salonen 2010). If the water from a bore well contains too much radon, households are recommended to primarily join the public water supply network. If this is not possible, there are several cleaning devices available based on aeration and active carbon filtration. The activated carbon filters should always be placed separately from the living quarters, as the radon degradation products accumulated in them transmit gamma radiation.

Water supply plants may consider replacement water abstraction from an abstraction plant with low radon concentration. Of the removal methods, aeration is the most economically feasible for water plants, as it is suitable for handling large amounts of water. Aeration removes not only radon but also other gases such as hydrogen sulphide and carbon dioxide from the water, which improves the taste and smell of the water. However, when aeration is used, it must be ensured that the radon concentration in the indoor air of the water plant does not become too high. At water supply plants, aeration can operate on three different principles: submerged, surface or gravity aeration. Activated carbon filtration is not usually used in water plants to remove radon.

8 Risk communication

One of the prerequisites of promoting radon safety is effective communication and training provided to stakeholders. The task of the radon working group comprised of representatives of the authorities is to provide the relevant authorities with information on training related to radon and to consider effective forms of radon communication. Reducing the risk of radon is important for public health and sufficient resources must be reserved for risk communication.

8.1 Risk awareness

Despite the considerable significance of radon exposure, few seem to be concerned about it. Meanwhile, some are very anxious and scared about radon. In other words, there is a lot of variation in conceptions of the risk posed by radon, which must be taken into consideration in communications.

According to a radon risk awareness survey conducted by STUK, 93% of the respondents had heard about radon and the majority considered it harmful, even though many associated wrong diseases or symptoms with radon exposure (Kojo et al. 2016). As many as 37% of the respondents had either negligent or negative attitudes towards radon measurements performed at their home. Smoking status did not correlate with the attitude towards the radon measurements. The Finnish Institute for Health and Welfare (Ung-Lanki and Lanki 2013) has also conducted a survey on the attitudes of Finns towards the risks in their living environment. According to the survey, most uncertainty is related to radon in respondents' views. When assessing the overall risk, the share of respondents choosing the alternative "I cannot say" was less than 6% for other environmental exposure agents, but 26% for radon. In the study, 50% of the respondents also felt that they knew little or nothing about the health risks associated with radon, and indoor air radon was considered to pose a relatively small risk to health.

It was clear that there was little awareness of the requirement to measure radon concentration in workplaces or other premises used by people, which was exemplified by the radon project carried out at day-care centres, in which a considerable share of day-care centres (61%) had not measured their radon concentrations even though the project was aimed at the municipalities bound by the measurement obligation (Kojo et al. 2015).

The United States Environmental Protection Agency has prepared a summary of the effectiveness of various radon campaigns (http://www.epa.ie/pubs/reports/research/health/Research_170_ wrapped.pdf). The review presents various means to ensure the effectiveness of a public information programme concerning radon. One of the recommended measures involved shifting responsibility solely from the householder and bringing in more government regulation in radon testing.

8.2 Targeting communications

In its statement on the Government proposal of the Radiation Act, the Parliament's Environment Committee emphasised the importance of advice and information in radon mitigation and new construction in detached houses, and that guidance by information should be directed particularly to those regions with high radon concentrations. The committee noted that municipal building control plays a crucial role in steering and advice related to the construction of single-family houses. In addition to the actual radon mitigation efforts, advice should be provided in contexts such as when updating ventilation systems in single-family houses from a natural ventilation to a forced ventilation system, which may have an impact on the radon concentration in indoor air. The committee also drew attention to the activities of real estate agents to ensure that, especially when selling single-family houses, the buyer would receive sufficient information about the possible radon risk. Providing information on radon concentrations should be part of good real estate practice similarly as condition inspections and asbestos testing.

In practice, the target audience for risk communication related to radon is all Finns. However, certain target groups can be identified and the information about risks provided to these groups can be carried out in a solution-oriented manner based on the starting points of each group. These include families with children, building owners and tenants, landlords, companies performing radon testing and mitigation,

construction companies, workplaces, real estate agents, NGOs (e.g. the Finnish Real Estate Federation, Finnish Real Estate Management Federation, Home Owners' Association, Finnish Society of Indoor Air Quality and Climate, cancer organisations), educational institutions (vocational education and training institutes, universities of applied sciences, universities), journalists, social media influencers, ministries and research institutes (e.g. Finnish Institute for Health and Welfare, Finnish Institute of Occupational Health, Finnish Safety and Chemicals Agency).

Non-smokers seem to be more eager to take radon mitigation measures, even if the corrections would be more effective for smokers in terms of reducing the risk of cancer. Nevertheless, there is no reason to only encourage smokers to take radon mitigation measures; smokers may at some point move to a house currently owned by non-smokers, and radon is the most significant cause of lung cancer in non-smokers. The aim is to have sufficiently low radon concentrations in all buildings, not only in those whose residents are smokers.

The supervisory authorities (building control, health protection, occupational safety and health) could plan radon communications at local level. Municipal building supervision plays a key role in the radon prevention of new buildings, and the specific target of risk communication is local construction activities, soil surveyors, soil and structural planners and persons performing the tasks of the main designer.

Indoor air radon concentrations vary and there may be significantly higher concentrations in some areas than elsewhere in the municipality. There is particular need to test and mitigation all dwellings and workplaces and premises used by people in the lowest floors of buildings located in these high-risk areas. However, it the communication, it is important to ensure that these areas will not become stigmatised as "dangerous" areas, which could even affect property prices.

8.3 Communication channels and methods

The websites of STUK and other authorities and expert institutions contain plenty of information related to the radon. Websites should be so clear and easy to use that citizens or other actors do not need to send individual messages to experts.

How issues related to radon are presented in the media is neither predictable nor decided by experts. While there is less need for traditional, printed publications these days, printed versions of key documents such as basic radon information and radon mitigation manuals should be available. Public hearings on various plans and documents under preparation helps taking the needs and perspectives of different groups into account in achieving the set targets. Social media is an important communication channel and should be utilised further.

In line with the international model, Finland could also designate a certain day or month as the radon security day or month, during which information about radon would be provided particularly efficiently. There is good reason to organise Radon Safety Days for professionals, including various radon experts providing information.

Risk communication must be considered as a dialogue between the participants.
An essential part of it is a process in which information and opinions related to risk management are taken into account. Naturally, such communication approach takes a lot of time and resources.

Appendix 1. Recommendations for action

Recommendation	Responsible party[3]
Long-term targets for reducing the risk of radon-induced lung cancer	
Improving the efficiency of cooperation between STUK, activities promoting wellbeing by municipalities, health protection, occupational health care and health care services in raising awareness of the risks of radon.	MSAH, Valvira, NGOs, THL, STUK, TTL
Making sure that radon in indoor air is a more visible part of the programmes concerning the health of indoor air and buildings, such as the Healthy Premises 2028 programme.	MSAH, ME, VNK, Ministry of Education and Culture
Ensuring that buildings are designed and constructed while ensuring radon safety across the country.	Construction supervision, land use planning and construction
Reference levels, statutes and developing enforcement	
The reference level will be included in the Decree of the Ministry of Social Affairs and Health on Health-related Conditions of Housing and Other Residential Buildings and Qualification Requirements for Third-party Experts in connection with the reform of the Decree.	MSAH
Utilising the national radon database in communications and targeting monitoring based on risks at the regional level or based on building types.	STUK, MSAH, Valvira
Investigating the interfaces between statutes related to radon and clarifying monitoring practices and making these run more smoothly based on the investigation.	MSAH, STUK, ME, Valvira, AVI, Association of Finnish Local and Regional Authorities
Improving the joint use of the databases of the authorities participating in radon supervision and expanding the access rights of the national radon database.	MSAH, STUK, ME, Valvira, AVI, Association of Finnish Local and Regional Authorities
Making efforts to also extend the national radon database to the results by private radon measurement providers. The aim is to also include comprehensive data about the radon measurements concerning other premises used by people and dwellings. Assessing legislation in this context.	MSAH, STUK

3 abbreviations: AVI Regional state administrative agency, areas of responsibility of health protection and occupational safety and health, MSAH Ministry of Social Affairs and Health, STUK Radiation and Nuclear Safety Authority, SYKE Finnish Environment Institute, THL Finnish Institute for Welfare and Health, TTL Finnish Institute of Occupational Health, Valvira National Supervisory Authority for Welfare and Health, VNK Prime Minister's Office, ME Ministry of the Environment

Recommendation	Responsible party[3]
Municipal health protection authorities ensure that regular monitoring is carried out with inspections that make sure that the radon concentration of other premises used by people has been measured.	MSAH, Valvira, AVI/health protection
If necessary, the regional state administrative agency's occupational safety and health authority will investigate whether exposure to radon has been taken into account as part of the investigation and evaluation of work hazards in an occupational safety and health inspection.	MSAH, AVI/health protection
Measurement	
Developing instructions for workplaces so that they will perform sufficiently comprehensive measurements right starting with the first time.	STUK
Investigating the annual and seasonal variation of air radon concentrations, and using the results to specify the practice used to determine the annual average.	STUK
Providing those involved in radon testing with training on performing measurements.	STUK
Assessing radon concentration in indoor air	
Finland's residential areas are not divided into different radon risk areas, as high radon concentrations can be found throughout Finland.	MSAH, Valvira, Association of Finnish Local and Regional Authorities
Reducing and preventing high radon concentrations	
The recommendation of the Ministry of the Environment is that in new construction, a party launching a construction project must ensure that radon concentration in indoor air is measured after building implementation. The recommendation concerns new workplaces and other public buildings and residential buildings.	parties carrying out construction projects
Radon prevention measures should be taken in connection with building renovation to the extent appropriate.	ME
Promoting ensuring that notifying of radon concentration is made a part of real estate sales (single-family houses and dwellings on the first floor of blocks of flats).	MSAH, STUK, ME, Valvira, AVI, Assoc. of Finnish Local and Regional Authorities
Carrying out a study on the long-term sustainability of radon prevention and mitigation efforts. E.g. whether the efficiency of radon prevention in new buildings and mitigation in older buildings has changed over time.	STUK

Recommendation	Responsible party[3]
Risk communication	
Ensuring that good radon guides and instructions are available.	STUK, MSAH, ME
Authorities increase communication and thus people's understanding of radon risks and the right approaches for protection against radon. Awareness of statutory obligations related to radon will also be raised. Organising public information campaigns and citizens' advice on radon.	MSAH, STUK, ME, Valvira, AVI, Assoc. of Finnish Local and Regional Authorities, health protection, building control
Raising awareness of the additional risk posed by radon to smokers as part of communications related to smoking.	MSAH, Valvira, NGOs, THL, STUK, TTL
Raising awareness of radon in well waters.	MSAH, Valvira, SYKE, STUK
Organising Radon Safety Days for radon professionals and the authorities and the general public.	STUK, MSAH, Valvira, AVI Assoc. of Finnish Local and Regional Authorities, radon testers

Appendix 2. Authorities participating radon regulatory control and their responsibilities

Radon in indoor air

Preliminary monitoring (radon safety monitoring as part of the building permit system)

1) Residential buildings, workplace buildings, other buildings
Responsible ministry: Ministry of the Environment

Supervisory authority: Municipal building control authority Monitoring subject: Party carrying out a construction project

Applicable law: Land Use and Building Act (132/1999)

Key provisions: Sections 117, 117c and 125, 153, 153a + Decree of the Ministry of the Environment on Foundation Structures, 465/2014, Decree of the Ministry of the Environment on the Indoor Climate and Ventilation of New Buildings 1009/2017

Monitoring description: Permit system for the construction of new buildings and extensive renovation and alteration of existing buildings, monitoring based on documents and inspections.

Post-monitoring (monitoring radon safety as part of monitoring of the built environment)

1) Dwellings and other premises used by people Responsible ministry: Ministry of Social Affairs and Health

Supervisory authority: Municipal health protection authority Monitoring subject/ responsible party: Owner or holder of dwelling Applicable law: Health Protection Act (763/1994)

Key provisions: Sections 26 and 27

Monitoring description: Monitoring based on documents and inspections of existing residential buildings and other premises used by people and health and safety in them.

2.1) Workplaces

Responsible ministry: Ministry of Social Affairs and Health Monitoring authority: Radiation and Nuclear Safety Authority Monitoring subject/responsible party: Employer Applicable law: Radiation Act (859/2018)

Key provisions: Chapter 18 of the Radiation Act; Government Decree on ionising radiation (1034/2018), Chapter 12; Ministry of Social Affairs and Health Decree on Ionising Radiation

(1044/2018), Chapter 6; Radiation and Nuclear Safety Authority's regulation on practice that causes exposure to natural radiation (S/3/2019)

Monitoring description: Monitoring based on documents and inspections concerning the radon exposure of employees working in workplace buildings.

2.2) Workplaces

Responsible ministry: Ministry of Social Affairs and Health Monitoring authority: Occupational safety and health authorities Monitoring subject: Employer

Applicable law: Occupational Safety and Health Act (738/2002)

Key provisions: Sections 8, 10, 38 and 39 of the Occupational Health Care Act (1383/2001) and the Act on Occupational Safety and Health Enforcement and Cooperation on Occupational Safety and Health at Workplaces (44/2006) Monitoring description: An occupational safety and health inspection includes examining whether radon exposure has been taken into account in the investigation and evaluation of the hazards of work, if necessary.

Radon in household wateR

Areas subject to monitoring in accordance with the Household Water Decree Responsible ministry: Ministry of Social Affairs and Health Monitoring authority: Municipal health protection authority

Monitoring subject/responsible party: Household water used or supplied for use as household water to be used in a water supply area for a minimum of 10 m^3 per day or serving the needs of at least 50 persons and water used as part of public or commercial activities or in food supply premises with its own well or other water source.

Applicable decree: Decree of the Ministry of Social Affairs and Health on the quality standards and regulatory control of household water (1352/2015)

Key provisions: Appendix 1, Table 3

Monitoring description: If the radon concentration exceeds the quality requirement, corrective action is necessary for radiation safety reasons, always without any further assessments regardless of the purpose of water use. The quality requirement of the Household Water Decree corresponds to the reference level referred to in the Radiation Act. The municipal health protection authority issues regulations as necessary by virtue of sections 20 and 51 of the Health Protection Act. If the radon quality target is not met, the necessity of corrective measures is considered on the basis of a risk assessment. If the radon activity concentration at the point of compliance is greater than 100 Bq/l, the concentration must be examined from raw water or water leaving a water treatment plant. The municipal health protection authority may request a risk assessment from STUK.

Areas subject to monitoring in accordance with the Small household Water Decree Responsible ministry: Ministry of Social Affairs and Health Monitoring authority: Municipal health protection authority

Monitoring subject/responsible party: Facilities supplying water to households supplying less than 10 m^3 of water per day or for less than 50 persons. Operators using water from their own water abstraction site, which is used as part of small-scale and low-risk public or commercial activities. Food processing premises that use water from their own water abstraction site if the activities are small-scale and low-risk.

Applicable decree: Decree of the Ministry of Social Affairs and Health on the quality standards and regulatory control of household water (401/2001)

Monitoring description: If necessary, the health protection authority will issue regulations to reduce radon concentration or introduce a replacement water source if concentrations higher than those specified in the quality recommendation are found.

Radioactivity of construction products

Responsible ministry: Ministry of Social Affairs and Health Monitoring authority: STUK

Monitoring subject/responsible party: Construction product manufacturer, transferor or importer Applicable law: Radiation Act

Key provisions: Section 153 of the Radiation Act, section 53 of the Government Decree on Ionizing Radiation and Chapter 4 of the STUK regulation (S/3/2019) Monitoring description: The manufacturer, transferor or importer of the construction product is responsible for the examination of the radioactivity of construction products at the STUK laboratory (construction products requiring testing are presented in section 53 of the Government Decree on Ionizing Radiation). If the radioactivity of the product does not comply with the condition of the regulation S/3/2019, the STUK laboratory sends the product's test report to the STUK's regulatory control. In this case, STUK will order the party responsible for the activities to investigate the radiation exposure caused by the construction product to the population in the intended use and based on realistic structural dimensions, or to dilute the product so that it meets the condition of regulation S/3/2019 before the product is used. STUK's regulatory control will also require the product information to include information about the radioactivity and instructions on how to ensure that exposure to radiation falls under the reference level. The decision is sent to the Finnish Safety and Chemicals Agency (TUKES) for information. The party responsible for the activities prepares and sends a report on the radiation exposure caused by the construction product to STUK's monitoring, in which calculations are checked before the product can be used for the intended purpose.

TUKES is responsible for monitoring the product information and CE markings of construction products. The Radiation Act requires that construction products that exceed the screening level must have a marking indicating radiation hazard and instructions ensuring that the reference level is not exceeded in the intended use.

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Radon is the second leading known cause of lung cancer after smoking. Exposure to radon increases the risk for developing lung cancers, particularly among smokers. Radon is also the most significant known cause of lung cancer among non-smokers. The majority of lung cancers could be prevented by stopping smoking and reducing exposure to radon. This Action Plan sets out long-term objectives and means for reducing the risk of lung cancer caused by radon in Finland. The main focus of this Action Plan is reducing radon concentration of indoor air radon, as the radon found in indoor air has commonly been the most significant source and cause of radiation exposure for Finns. Radon gas found in indoor air is released from the soil and bedrock underneath or surrounding buildings, building materials or borehole water. This Action Plan is based on Article 103 of the Directive for protection against the dangers arising from exposure to ionising radiation (2013/59/Euratom), which requires Member States to draw up a National Action Plan to prevent long-term risks from radon. In Finland, this obligation has been implemented with section 159 of the Radiation Act (859/2018). Further provisions on the Action Plan and its content are laid down in the Government Decree on Ionising Radiation (1034/2018, section 54 and Annex 6).

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