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Assessment of current techniques used for reduction of indoor radon concentration in existing and new houses in European countries

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RADPAR

WP6: Assessment of radon control technologies

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Key words: radon, indoor air, dwellings, radon remediation, radon prevention

Abstract

Radon control technologies aim at the reduction of indoor radon concentrations in existing buildings and in new construction through remedial and preventive measures. In recent years, rising ecological awareness and rising energy costs have stimulated the development of low energy and passive houses to save energy. This report contains the analysis and assessment of current techniques and technologies used to achieve the reduction of indoor radon concentrations in existing and new houses with regard to the reduction efficiency and potential impact on energy consumption (qualitative analysis).

A questionnaire was prepared and sent to all RADPAR partners in 14 different countries in order to gather national information about the current remediation and prevention techniques. Responses with variable amounts of information were obtained. Based on the questionnaire responses, the status of radon remediation and prevention in each country was assessed, in addition to the reduction efficiency and potential impact on energy consumption of the current remediation and prevention techniques.

The number of dwellings with an elevated indoor radon concentration typically ranges from tens of thousands to a million. The percentage of these houses already remediated varies from zero to 15%. Preventive measures in new construction have been taken from a small number of houses to over half a million houses. The research data on the current situation, the number of houses with preventive measures and the efficiency of these measures is currently still quite inadequate. Assessment of the techniques and also the surveys aiming at exploring the impact of remedial and preventive measures is greatly needed in order to promote the work at the national level.

The most efficient remediation method is the active sub-slab depressurization (SSD) and the radon well, for which the reduction in the radon concentration is typically 70–95%. Other methods, such as sealing entry routes and improving ventilation in living spaces, in the cellar or in the crawl space, are less effective: the reduction in the radon concentration is typically 10–60%. The efficiencies of prevention techniques are analogous to those of remediation

techniques. Active SSD is the most efficient prevention technique. The efficiency of passive SSD and passive radon piping is lower, typically 20–50%. However, widespread use of such systems can be recommended. Radon-proof membrane in the base floor reduces the radon concentration on average by 50%.

The impact of remedial techniques and preventive techniques on energy consumption is significant for active SSD, mainly due to the power consumption of the electrical fan used and potentially also to a lesser degree due to cooling of the base floor. The impact on energy consumption of passive SSD and passive radon piping is negligible. Sealing entry routes in both remediation and prevention in new construction has a positive impact through reduction of the leakage of cold air from the ground in low energy and passive houses. Replacing existing natural or mechanical exhaust ventilation with a new mechanical supply and exhaust ventilation system with heat recovery typically reduces energy consumption. On the other hand, other methods increasing ventilation in living spaces reduce the radon concentration, but simultaneously increase energy consumption due to increased air exchange.

Sealing the constructions of house foundations in contact with soil and the control of air flows in standard, low energy and passive construction have synergistic goals. Reduction of soil-air flows into the house reduces indoor radon concentrations and simultaneously also the energy consumption.

HOLMGREN Olli, ARVELA Hannu. Radonkorjaus- ja torjuntamenetelmät Euroopassa – kyselytutkimus 2010. STUK-A251. Helsinki 2012, 82 s. + liitteet 20 s.

Avainsanat: radon, sisäilma, asunnot, radonkorjaukset, radontorjunta

Tiivistelmä

Radonkorjaus- ja radontorjuntamenetelmillä pyritään alentamaan radonpitoisuutta vanhoissa ja uusissa rakennuksissa. Viime vuosina on kiinnitetty huomiota rakennusten energiatehokkuuden parantamiseen. Tässä raportissa arvioidaan nykyisten radonkorjaus- ja torjuntamenetelmien tehokkuutta alentaa radonpitoisuutta sekä niiden vaikutusta rakennusten energiankulutukseen. Hankkeessa tehtiin kyselytutkimus 14 osallistujamaassa. Kyselyllä hankittiin maakohtaista tietoa edellä mainittuihin kysymyksiin sekä kunkin maan radonkorjaus- ja torjuntatilanteesta. Vastauksissa oli vaihteleva määrä tietoa.

Osallistujamaissa kansallisen enimmäisarvon ylittävien asuntojen määrä on tyypillisesti kymmenistä tuhansista miljoonaan. Jo korjattujen asuntojen osuus näistä vaihtelee nollasta 15 %:iin. Uudisrakentamisen torjuntatoimia on toteutettu hyvin pienestä määrästä aina puoleen miljoonaan asuntoon. Tutkimustieto, joka koskee asuntoja, joissa on tehty torjuntatoimia ja näiden toimien tehokkuutta on vielä hyvin puutteellista.

Tehokkaimpia torjuntatoimenpiteitä ovat radonimuri ja radonkaivo, joille tyypilliset radonpitoisuuden alenemat ovat 60–95 %. Muut menetelmät kuten vuotoreittien tiivistäminen ja asuintilojen, kellarin tai ryömintätilan ilmanvaihdon parantaminen ovat vähemmän tehokkaita: tyypilliset alenemat ovat 10–60 %. Torjuntatoimenpiteiden tehokkuudet ovat analogisia korjaustoimenpiteiden kanssa. Imurilla varustettu radonputkisto tai imukuoppa on tehokkain menetelmä. Passiivisessa järjestelmässä ei ole imuria ja sen tehokkuus on alhaisempi, tyypillisesti 20–50 %. Kuitenkin passiivisen järjestelmän laajaa käyttöä suositellaan. Kermien käyttö alapohjan tiivistämisessä alentaa radonpitoisuutta keskimäärin 50 %.

Radonkorjaus- ja torjuntamenetelmien vaikutus asunnon energiankulutukseen on merkittävin radonimurilla pääasiassa sähköisen puhaltimen takia, mutta mahdollisesti myös alapohjan jäähtymisen takia. Passiivisen radonputkiston vaikutus asunnon energiankulutukseen on pieni. Rakenteiden tiivistäminen erityisesti matalaenergia- ja passiivienergiataloissa pienentää asunnon energiantarvetta vähentämällä hallitsemattomia kylmän ilman vuotoja. Vanhan painovoimaisen ilmanvaihdon korvaaminen uudella lämmön

talteen ottavalla koneellisella tulo- ja poistoilmanvaihdolla pienentää myös asunnon energiankulutusta. Toisaalta muut ilmanvaihtoa lisäävät menetelmät pienentävät radonpitoisuutta, mutta samalla ne lisäävät asunnon energiantarvetta.

Talon perustusten tiivistämisellä radontorjunnassa ja matala- ja passiivienergiatalon ilmanvaihdon ilmavirtojen hallinnalla on yhteinen tavoite. Vähentämällä maaperästä sisälle virtaavan ilman määrää asunnon radonpitoisuus ja samalla myös energiankulutus pienenee.

Contents

1 Introduction

This report arises from the project "Radon prevention and remediation" (RADPAR), which has received funding from the European Union, in the framework of the Health Programme. The general objective of this three-year project is to assist in reducing the significant public health burden of radon-related lung cancers in EU Member States (MS).

The main source of indoor radon in most buildings is the subjacent soil gas, while the building materials in most cases make only a smaller contribution. The level of radon in a building is, however, to a large extent influenced by the properties of the building itself and its usage. Critical building parameters include coupling to the ground, the air exchange rate, the leakage distribution of the building envelope, the type of heating/ventilation system and the living comfort preferences of the occupants.

Present methods for radon reduction in existing buildings and radon prevention in new buildings have been developed over the last 25 years. While most techniques using sumps and barriers should work in principle, the limited evidence presently available has shown that there is considerable variability in their effectiveness. Defective installation and poor adherence to the relevant building code guidelines are major contributors to this problem in some MS.

In recent years, rising ecological awareness and rising energy costs have stimulated the development of low energy and passive houses to save energy. It can be expected that these types of houses will represent an ever increasing proportion of the new housing stock. However, certain construction, heating and ventilation techniques used in these houses have the potential to lead to high indoor radon levels. On the other hand, remediation techniques such as enhancing air exchange or using fans could have a negative impact on energy consumption. Since the prevention of high radon levels in new buildings is an important component of any national radon strategy, it is essential to evaluate the effect of new construction methods on the indoor radon level. Examples of potential problematic construction features with respect to radon exposure include the reduction of air exchange due to new energy saving regulations, heat exchange systems in contact with soil, and permeable construction materials.

In order to evaluate the above discussed problems concerning the radon control, to reduce potential conflicts between energy saving construction and radon reduction, and to inform building professionals, the following objectives were carried out in RADPAR Work Package (WP) 6: 1) Assessment of potential conflicts between energy conservation in buildings and radon exposure reduction; 2) Establishment of measurement protocols for radon control technologies; and 3) Design of training courses for radon measurement, prevention, remediation, and cost effectiveness analysis. A questionnaire dealing with these issues was sent to all RADPAR partners in 14 different countries.

This report contains the analysis and assessment of current techniques/technologies used to achieve the reduction of indoor radon concentrations in existing and new houses with regard to reduction efficiency and the potential impact on energy consumption (qualitative analysis). It serves as a basic background study for the objectives of WP 6 as well as for other RADPAR work packages. In section 2, the questionnaire is briefly discussed. In Section 3, the national situation in each of the RADPAR partner countries is summarized, including action and reference levels for radon remediation and prevention, estimates on the number of dwellings exceeding the action level and those already remediated, typical radon remediation and prevention methods with reduction efficiencies, and references to guides, publications, websites and other relevant documents. In Section 4, an overview of remediation techniques is presented, focusing on reduction efficiency and qualitative analysis of the potential impact on energy consumption. Section 5 gives an overview of the prevention techniques used in new buildings, including reduction efficiency and qualitative analysis of the potential impact on energy consumption. Section 6 contains a summary of current techniques used to achieve the reduction of indoor radon concentrations in existing and new houses. Detailed questionnaire data and the original questionnaire are tabulated in the Appendices.

2 Questionnaire

The questionnaire of this study attached in Appendix 2 was sent to all RADPAR partners in 14 different countries (Austria, Belgium, the Czech Republic, Finland, France, Germany, Greece, Ireland, Italy, Norway, Portugal, Spain, Switzerland, and the UK). Responses with variable amounts of information were obtained. The master questionnaire prepared by WP 5 was also utilized in the assessment.

The questionnaire was divided into two parts: remediation of existing dwellings and prevention in new construction. Each part contained a set of questions relating to the following:

1. National situation: action (target) levels for radon remediation (prevention), Number of dwellings exceeding the action level, number of houses with remediation (or prevention) measures.
2. Methods used for remediation (or prevention), reduction factors for each method and any qualitative information on the potential impact on energy consumption.
3. References: guides, brochures, research reports, website links and other relevant documentation.

In addition, there was a third part for additional information.

The radon reduction factor R in [%] (or reduction efficiency) is defined by

$$R = \frac{C_{before} - C_{after}}{C_{before}} \cdot 100 \quad [\%], \tag{1}$$

where C_{before} and C_{after} are indoor radon concentrations [Bq/m^3] before and after remediation (or without and with the prevention method).

The reduction efficiency is sometimes reported as a reduction factor RF defined by

$$RF = \frac{C_{before}}{C_{after}}. \tag{2}$$

Combining equations (1) and (2), R can be calculated from RF using the following equation:

$$R = \left(1 - \frac{1}{RF}\right) \cdot 100.$$

3 National situation

3.1 Austria

Regulations and guidance

The action level for radon remediation is 400 Bq/m^3 and the recommended target level in new buildings is 200 Bq/m^3.

There are national standards for remedial and preventive measures:

- ICS 13.280 Radon – Part 3: Remedial measures on buildings. (In German)
- ICS 13.280 Radon – Part 2: Technical precautionary measures in the case of buildings. (In German)

Status of remediation and prevention

Table 1 presents the estimated number of dwellings exceeding the action level and the number of dwellings in which remediation measures have been applied.

Table 1. Status of radon remediation in Austria.

	In low-rise residential buildings[1]	In apartment buildings
Estimated number of dwellings	1 900 000	1 800 000
Estimated number of dwellings exceeding the action level	80 000	9 000
Estimated number of dwellings already remediated	25	0

[1] Low rise residential buildings: detached, semi-detached and row/terraced houses.

It was estimated that preventive measures have been applied in 15 houses.

Technologies used for remediation of existing buildings

The remediation methods used in Austria and the reduction factors of the methods reported in the questionnaire response are given in Table 2. In the questionnaire it was also commented that sealing of entry routes is typically used in combination with sub-slab depressurization.

Table 2. Reduction factors of radon remediation methods reported in the questionnaire by Austria.

Remediation method	Reduction factor (%), typ. range
Sub-slab depressurization	80
Installation of a new mechanical supply and exhaust ventilation system with heat recovery	60
House pressurization (higher pressure indoors than in the soil under the floor)	80
Improving cellar ventilation	50
Reducing under-pressure in the house	50
Sealing entry routes	10
Improving crawl space ventilation	50
Sealing + sub-slab depressurization	80
Sealing + new mechanical supply and exhaust ventilation + house pressurization + reducing under-pressure	80

Technologies used for prevention in new construction

The prevention methods used are passive and active sub-slab depressurization, radon-proof barrier with a membrane below or above the floor slab, sealing the joint of the floor slab and foundation wall using membranes, and sealing of pipe penetrations in structures with soil contact. In addition, the use of waterproof concrete instead of normal concrete was reported.

These methods are recommended (usually in combination), but there has been no follow-up to check whether the methods have actually been implemented and what impact they have had on radon and energy consumption.

Selected list of publications

Friedmann H. Final results of the Austrian Radon Project. Health Physics 2005; 89 (4): 339–348.

ICS 13.280 Radon – Part 3: Remedial measures on buildings. (In German, Austrian Standards)

ICS 13.280 Radon – Part 2: Technical precautionary measures in the case of buildings. (In German, Austrian Standards)

Maringer FJ, Akis MG, Kaineder H, Kindl P, Kralik C, Lettner H, Lueginger S, Nadschläger E, Ringer W, Rolle R, Schönhofer F, Sperker S, Stadtmann H, Steger F, Steinhäusler F, Tschurlovits M, Winkler R. Results and conclusions of the Austrian radon mitigation project 'SARAH'. The Science of The Total Environment 2001; 272 (1–3): 159–167.

Website links

www.strahlenschutz.gv.at (In German)

3.2 Belgium

Regulations and guidance

The action level for radon remediation is 400 Bq/m^3 and the recommended target level in new buildings is 200 Bq/m^3.

Guides for remediation and prevention are:

- Le Radon et votre habitation: méthodes de remédiation et de prévention, 30 pp., AFCN.
- Le radon dans les habitations: mesures préventives et curatives – Note d'information technique 211, Centre Scientifique et Technique de la Construction, 1999.

Status of remediation and prevention

Table 3 presents the estimated number of dwellings exceeding the action level and the number of dwellings in which remediation measures have been applied.

Table 3. Status of radon remediation in Belgium.

	In low-rise residential buildings	In apartment buildings
Estimated number of dwellings	3 612 000 In radon-prone zone: 68 000	1 431 000
Estimated number of dwellings exceeding the action level	20 000 In radon-prone zone: 10 000	
Estimated number of dwellings already remediated	<1 000	

The number of houses with radon prevention is not known.

Technologies used for remediation of existing buildings

The remediation methods used and the reduction factors of the methods reported in the questionnaire response are given in Table 4.

Table 4. Reduction factors of radon remediation methods reported in the questionnaire by Belgium.

Remediation method	Reduction factor (%), typ. range
Sub-slab depressurization	90
Improving mechanical ventilation in living spaces	Low
Improving cellar ventilation	Limited
Sealing entry routes	Sometimes effective
Improving crawl space ventilation	

Technologies used for prevention in new construction

The prevention methods used are passive and active sub-slab depressurization, radon-proof barrier with a membrane below or above the floor slab and sealing of pipe penetrations in structures with soil contact.

Selected list of publications

Le radon dans les habitations: mesures préventives et curatives – Note d'information technique 211. Belgium: Centre Scientifique et Technique de la Construction; 1999.

Le Radon et votre habitation: méthodes de remédiation et de prévention. Federal Agency for Nuclear Control, Belgium.

Website links

www.fanc.fgov.be
www.ibes.be/radon
www.ecoterra.be

3.3 Czech Republic

Regulations and guidance

The action level for radon remediation is 400 Bq/m^3 and the recommended target level in new buildings 200 Bq/m^3. There is a lower limit of 1 000 Bq/m^3 for gaining a state financial grant of up to 5 600 EUR for radon remediation.

In the Czech Republic, all types of radon protective and remedial measures should be designed and installed in accordance with the Czech national standards (in Czech):

- ČSN 730601 Protection of houses against radon from the soil.
- ČSN 730602 Protection of houses against radon and gamma radiation from building materials.

In the standards, the principles of design and application of various types of radon reduction techniques are presented. The degree of radon protection depends on the type of building and on the results of pre-installation diagnosis (Jiránek 2003).

Status of remediation and prevention

Table 5 presents the estimated number of dwellings exceeding the action level and the number of dwellings in which remediation measures have been applied. The values have been adopted from the RADPAR master questionnaire.

Table 5. Status of radon remediation in the Czech Republic.

	In low-rise residential buildings	In apartment buildings
Estimated number of dwellings	1 640 000	2 200 000
Estimated number of dwellings exceeding the action level	76 440	
Estimated number of dwellings already remediated	4 000	

It was estimated that in approximately 2/3 up to 4/5 of new houses, preventive measures should be applied. Assuming an average of 16 000 new houses with preventive measures annually since 1997, this yields a total of 210 000 such houses.

Technologies used for remediation of existing buildings

In existing buildings, a set of diagnostic measurements must be performed to identify radon entry routes into the building and radon pathways inside the building and to prepare information for the effective design of remedial measures. The set usually comprises measurement of the radon concentration in all rooms, determination of the radon index of the building site, assessment of the radon concentration and permeability of sub-floor layers and other reasonable and helpful measurements.

The type of remediation depends on the indoor radon concentration, type of house and applicability of the measure to the existing structure. Buildings only slightly exceeding the guidance levels (indoor radon concentration is below 600 Bq/m^3) can be easily and inexpensively mitigated by sealing the radon entry routes, improving the cellar–outdoor ventilation, preventing air movement from the cellar to the first floor, improving the indoor–outdoor ventilation, and creating a slight overpressure within the building.

Buildings with an indoor radon concentration above 600 Bq/m^3 should be remediated by more effective methods. The basic and the most effective solution is the installation of a sub-slab depressurization system. The preference should be given to systems that can be installed without the reconstruction of floors and obstructions within the living space. In houses with damp walls and floors, the best solution could possibly be the installation of ventilated air gaps or replacement of existing floors by new ones in which radon-proof membrane and a soil ventilation system are combined.

Passive ventilation of soil or air gaps is usually not sufficient, and active ventilation is therefore recommended. Passive systems must be installed in such a way that they can be very easily activated with a fan. Similarly, radon-proof membrane as a single measure is not so effective, because it cannot usually be applied under the walls, and radon can thus still be transported through wall–floor joints. Therefore, combination with a soil ventilation system is recommended.

The reduction factors of the remediation methods reported in the questionnaire response are given in Table 6.

Table 6. Reduction factors of radon remediation methods reported in the questionnaire by the Czech Republic.

Remediation method	Reduction factor (%), typ. range
Sub-slab depressurization	85 – 95
Improving natural ventilation in living spaces	< 30
Installation of a new mechanical supply and exhaust ventilation system with heat recovery	30 – 60
Improving cellar ventilation	25 – 50
Sealing entry routes	10 – 40
New floors with radon-proof membrane	35 – 45
Active floor air gap ventilation	70 – 85
New floors with radon-proof membrane + sub-slab depressurization	85 – 95
New floors with radon-proof membrane + floor air gap depressurization	80 – 90

Technologies used for prevention in new construction

The way in which protection is carried out depends on the type of building, its position in the soil profile, and the so-called “radon index” of the building site. Classification into one of three categories of the radon index (low, medium and high) is based on the soil gas radon concentration and soil permeability measurements carried out directly on the building site of each house. If the radon index is higher than low, the building must be protected against radon penetration from the ground.

The basic protective measure is a radon-proof membrane applied continuously over the entire surface of the floors and basement walls in contact with the soil. All joints and pipe penetrations through the radon barrier must be carefully sealed. The radon barrier acts at the same time as a damp-proof material. The only materials that may be used as radon-proof membranes are those with barrier properties that have been verified by measuring the radon diffusion coefficient, and that have proven durability corresponding to the expected lifetime of the building. Bitumen membranes with Al foil cannot serve as a radon-proof membrane due to their very low tear resistance, and plastic membranes with dimples are unsuitable due to evidence that it is almost impossible to form airtight joints with this material. The minimal thickness of the radon-proof membrane is calculated according to the standard ČSN 730601 depending on particular conditions, e.g. soil and building characteristics (Jiránek 2008 AARST).

According to the standard ČSN 730601, a radon-proof membrane as a single measure is only sufficient if the third quartile of soil gas radon concentrations measured on the building site is lower than:

- 60 kBq/m^3 in highly permeable soils,
- 140 kBq/m^3 in soils with a medium permeability,
- 200 kBq/m^3 in soils with a low permeability.

If the above-mentioned limits are exceeded, a radon-proof membrane must be provided in combination with other measures, such as sub-slab depressurization systems or ventilated air gaps provided along walls and floors in contact with soil. Sub-slab depressurization is usually formed by a network of flexible perforated pipes placed in a sub-floor layer of coarse gravel. Perforated pipes are connected to a vertical exhaust pipe, which terminates above the roof. In most cases, the floor air gap is implemented under a radon-proof membrane. The best solution is to ventilate the air gap above the roof. Natural or forced ventilation can be used.

The reduction factors of the prevention methods reported in the questionnaire response are given in Table 7.

Table 7. Reduction factors of radon prevention methods reported in the questionnaire by the Czech Republic.

Prevention method	Reduction factor (%), Typ. range
Radon-proof barrier, membrane above floor slab	30–70
Radon-proof membrane above floor slab + active or passive sub-slab ventilation	40–80

Selected list of publications

ČSN 730601 Protection of houses against radon from the soil (Czech standard).

ČSN 730602 Protection of houses against radon and gamma radiation from building materials (Czech standard).

Jiránek M. Radon remedial and protective measures in the Czech Republic according to the Czech standards ČSN 73 0601 and ČSN 73 0602. Praha, Czech Republic: Czech Technical University, Faculty of Civil Engineering; 2003.

Jiránek M. Forms of sub-slab depressurization systems used in the Czech Republic. In: Radon investigations in the Czech Republic X. 2004 Sep 15–18; Praha, Czech Republic. p. 119–125.

Jiránek M. Consequences of incorrect design and unqualified realization on reliability and effectiveness of radon reduction measures. In: Radon investigations in the Czech Republic and the 8th international workshop on the Geological Aspects of Radon Risk Mapping. 2006 Sep 26–30; Praha, Czech Republic. p. 123–130.

Jiránek M, Fronka A. New technique for the determination of radon diffusion coefficient in radon-proof membranes. Radiation Protection Dosimetry 2008; 130 (1): 22–25.

Jiránek M, Hůlka J. Applicability of various insulating materials for radon barriers. The Science of the Total Environment 2001; 272: 79–84.

Jiránek M, Neznal M. Mitigation of houses with extremely high indoor radon concentrations. In: Proceedings of the Second European IRPA Congress on Radiation Protection. 2006 May 15–19; Paris, France.

Jiránek M, Rovenská K. Limited applicability of cost-effectiveness and cost-benefit analyses for the optimization of radon remedial measures. Journal of Hazardous Materials 2010; 182 (1–3): 439–446.

Jiránek M, Svoboda Z. Numerical modelling as a tool for optimisation of sub-slab depressurisation systems design. Building and Environment 2007; 42: 1994–2003.

Jiránek M, Svoboda Z. Transient radon diffusion through radon-proof membranes: A new technique for more precise determination of the radon diffusion coefficient. Building and Environment 2009; 44 (6): 1318–1327.

Jiránek M, Neznal M, Neznal M. Mitigation of ineffective measures against radon. Radiation Protection Dosimetry 2008; 130 (1): 68–71.

Jiránek M, Rovenská K, Froňka A. Radon diffusion coefficient – a material property determining the applicability of waterproof membranes as radon barriers. In: Proceedings of the American Association of Radon Scientists and Technologists (AARST) 2008 International Symposium. 2008 Sep 14–17; Las Vegas, NV, USA.

Website links

www.suro.cz/en/prirodnioz

3.4 Finland

Regulations and guidance

The action level for radon remediation is 400 Bq/m^3 and the target level in new buildings 200 Bq/m^3. The target level has been mandatory since 2004.

The first indoor radon remediation studies were carried out in the mid-1980s. These studies resulted in the first remediation reports, which provided general information on active sub-slab depressurization systems. Both the Radiation and Nuclear Safety Authority (STUK) and the Ministry of the Environment published the first remediation guides in the 1990s. The Ministry guide focused on the sub-slab depressurization system, its design and implementation. The STUK guide, revised in 2008, provides an overview of different remediation methods, referring to the ministry guide, and presents the results achieved.

- Arvela H, Reisbacka H. Asuntojen radonkorjaaminen (Indoor radon mitigation). STUK-A229. Helsinki: Radiation and Nuclear Safety Authority; 2008. (In Finnish, abstract in English, national mitigation guide, 131 pp.). Swedish translation of STUK-A229 published as STUK-A237 in 2009.
- Radon remediation of low-rise residential houses. Sub-slab depressurization. Ministry of the Environment. Environmental guide 4. Helsinki: Edita; 1996. (In Finnish. 44 pp.)

The main reason for elevated indoor radon concentrations is radon-bearing soil air. To prevent the entry of soil air into indoor air, the National Building Code of Finland requires radon-resistant design and construction in new buildings across the whole country. For technical guidelines, the Code refers to the Guide for Radon Prevention (Building Information Ltd 2003).

- Radon-resistant new construction. RT Building File, RT 81-10791. Helsinki: Building Information Ltd; 2003. (In Finnish, 16 pp.)
- National Building Code of Finland (Ministry of the Environment)
    - B3 Foundations, regulations and guidelines 2004 (unofficial English translation available)
    - D2 Indoor climate and ventilation of buildings, Regulations and guidelines 2010.

Status of remediation and prevention

Table 8 provides the estimated number of dwellings exceeding the action level and the number of dwellings in which remediation measures have been applied (from the RADPAR master questionnaire). The action level is exceeded in approximately 59 000 dwellings, i.e., 2.4% of all dwellings. The estimated number of houses where preventive measures have been taken is 60 000.

Table 8. Status of radon remediation in Finland.

	In low-rise residential buildings	In apartment buildings
Estimated number of dwellings	1 350 000	1 100 000
Estimated number of dwellings exceeding the action level	51 000	8 000
Estimated number of dwellings already remediated	4 200	300

Technologies used for remediation of existing buildings

Sub-slab depressurization (SSD) and radon wells are the most efficient methods used. Typical reduction factors for both methods are 70–90% (see Table 9). In difficult cases, additional sealing work is needed in order to achieve low radon concentrations. SSDs have been implemented through both the floor slab and foundation wall. The activation of preparatory radon piping (a network of perforated pipes installed during construction) by an exhaust fan has also resulted in high reduction factors, typically 75–95%.

Table 9. Reduction factors of remediation methods reported in the questionnaire by Finland. The values are 25%–75% percentiles of the results achieved.

Remediation method	Reduction factor (%), typ. range
Sub-slab depressurization	65–95
Improving natural ventilation in living spaces	15–55
Improving mechanical ventilation in living spaces	5–55
Replacing the existing natural room air ventilation with mechanical exhaust ventilation	15–45
Installation of a new mechanical supply and exhaust ventilation system with heat recovery	30–65
Improving cellar ventilation	20–55
Sealing entry routes	10–55
Improving crawl space ventilation	40–65
Radon well (soil ventilation, outside the house)	80–90
Stop using water from drilled well	25–55
Several methods used	35–75

A radon well is constructed outside of the house, and the well sucks air from the soil from a depth of 4–5 m. This ventilation efficiently reduces the radon concentration of soil air below the house foundation. A single radon well can reduce the radon concentration in many dwellings at a distance of up to 20–30 m. A radon well is only effective in soils where the air permeability is high enough, e.g., on gravel and in esker areas.

Radon reduction methods based on ventilation reduce the radon concentration either through increased ventilation (dilution) or lowering the under-pressure of the house. A reduction factor above 50% has only been achieved in cases where the original air exchange rate has been defective or when the house under-pressure has been high. Typical reduction factors have been 10–40%. Increasing the operation time or power of mechanical ventilation and opening existing or installing new fresh air vents are typical measures. The installation of new fresh-air vents usually reduces the radon concentration by < 50%.

The sealing of entry routes aims at reducing leakage flows of radon-bearing soil air into living spaces. Sealing may be very demanding. In many cases, the results are only satisfactory when the entry routes have been almost completely sealed. The best results have been achieved in houses where the foundation wall is of cast concrete. Floor joints with foundation walls of porous lightweight concrete cannot be sealed with normal methods. Typical reduction factors have been 10–55%. The improvement of crawl space ventilation has also been used, with a reduction factor of 40–65%. Household water from a drilled well can be one source of radon in some dwellings. Fixing this problem typically lowers the radon concentrations by 25–55%.

Technologies used for prevention in new construction

The emphasis is on radon prevention in the case of the most common substructure, i.e. slab-on-ground. The most important measures are sealing with reinforced bitumen felt and the installation of radon piping (a network of perforated pipes beneath the building), discussed in the Guide for Radon Prevention.

Reinforced bitumen felt is used for sealing the joint of the slab-on-ground and the foundation wall, and walls in contact with soil in houses with a basement or semi-basement. Penetrations of, for instance, water pipes and electric cables are sealed airtight using elastic sealing compounds. The walls in contact with soil and made of lightweight concrete blocks are plastered on both sides, after which reinforced bitumen felt is attached on the outside surface of the wall.

The radon piping is installed under the slab, and an exhaust duct is connected to the piping. The exhaust pipe running up through the house is recommended to be kept open on the roof. If the indoor radon level still exceeds 200 Bq/m^3, the piping can be activated by connecting a fan to the exhaust duct.

The National Building Code of Finland and the associated practical guidelines for radon prevention were revised in 2003 to 2004. Thereafter, preventive measures have become more common and prevention practices more effective. In order to explore the situation, STUK carried out a nationwide sample survey in 2009 (Arvela et al. 2011). In this study, indoor radon concentration was measured in 1 561 new low-rise residential houses. The houses were randomly selected and represent 7% of houses that received building permission in 2006. According to the results preventive measures had been carried out in 54% of single family houses with slab on ground. Passive radon piping with an open exhaust (i.e., passive SSD) lowers the radon concentration on average by 40% (see Table 10). Activating the radon piping further reduces the radon concentration by 70–90%. A combination of passive radon piping and sealing of the joint between the floor slab and foundation wall using bitumen felt reduces the radon concentration by 55% on average. The installation of radon piping has become increasingly common in houses built during the last ten years.

Table 10. Reduction factors of radon prevention methods reported in the questionnaire by Finland. The reduction factors are 25%–75% percentiles of the results achieved.

Prevention method	Reduction factor (%), typ. range
Passive sub-slab depressurization	30–40
Active sub-slab depressurization	70–90
Passive SSD & sealing the joint between floor slab and foundation wall with bitumen felt	40–60

Selected list of publications

Arvela H. Experiences in radon-safe building in Finland. The Science of the Total Environment 2001; 272 (1–3): 169–174.

Arvela H. Radon mitigation in blocks of flats. The Science of the Total Environment 2001; 272 (1–3): 137.

Arvela H. Indoor radon sources, remediation and prevention in new construction. Refresher course. In: Proceedings – Third European IRPA Congress, 14–18 June 2010, Helsinki, Finland. Helsinki: Radiation and Nuclear Safety Authority (STUK) / Nordic Society for Radiation Protection (NSFS); 2011. R12. p. 2991–3013. [PDF publication]

Arvela H, Hoving P. Finnish experiences in indoor radon mitigation. In: Proceedings of the 6th International Conference on Indoor Air Quality and Climate. Vol. 4. 1993 July 4–8; Helsinki, Finland. p. 563–568.

Arvela H, Reisbacka H. New indoor radon mitigation guides in Finland. In: Nordic Society for Radiation Protection – NSFS. Proceedings of the NSFS XV conference in Ålesund Norway, 26– 30 of May 2008. StrålevernRapport 2008:13. Østerås: Norwegian Radiation Protection Authority; 2008. p. 121–124.

Arvela H, Reisbacka H. Asuntojen radonkorjaaminen (Indoor radon mitigation). STUK-A229. Helsinki: Radiation and Nuclear Safety Authority; 2008. (In Finnish, abstract in English, national mitigation guide)

Arvela H, Reisbacka H. Radonsanering av bostäder (Indoor radon mitigation). STUK-A237. Helsinki: Radiation and Nuclear Safety Authority; 2009. (In Swedish, translation of STUK-A229)

Arvela H, Bergman J, Yrjölä R, Kurnitski J, Matilainen M, Järvinen P. Developments in radon-safe building in Finland. Radioactivity in the environment 2005; 7: 618–623.

Arvela H, Reisbacka H, Keränen P. Radon prevention and mitigation in Finland: Guidance and practices. In: Proceedings of the American Association of Radon Scientists and Technologists AARST 2008 International Symposium. 2008 Sep 14–17; Las Vegas NV, USA. (Available at *www.aarst.org*)

Arvela H, Mäkeläinen I, Holmgren O, Reisbacka H. Radon prevention in new construction – Sample survey 2009. STUK-A244. Helsinki: Radiation and Nuclear Safety Authority (STUK); 2010. (In Finnish, abstract in English and Swedish)

Arvela H, Holmgren O, Reisbacka H. Radon prevention in new construction in Finland: a nationwide sample survey in 2009. Radiation Protection Dosimetry 2012; 148 (4): 465–474.

Keränen P, Arvela H. Radon resistant construction in Finland in 2007. In: Nordic Society for Radiation Protection – NSFS. Proceedings of the NSFS XV conference in Ålesund Norway, 26–30 of May 2008. StrålevernRapport 2008:13. Østerås: Norwegian Radiation Protection Authority; 2008. p. 125–129.

National Building Code of Finland (Ministry of the Environment): B3 Foundations, regulations and guidelines 2004 (unofficial English translation available), and D2 Indoor climate and ventilation of buildings, Regulations and guidelines 2010 (unofficial English translation available, 2003).

Radon remediation of low-rise residential houses. Sub-slab-depressurization. Ministry of Environment. Environmental guide 4. Helsinki: Ministry of Environment; 1996. (In Finnish)

Radon resistant new construction. RT-Building File, RT 81-10791. Helsinki: Building Information Ltd; 2003. (In Finnish)

Reisbacka H. Radon mitigation in large buildings in Finland. In: Valentin J, Cederlund T, Drake P, Finne IE, Glansholm A, Jaworska A, Paile W, Rahola T (eds). Radiological Protection in Transition – Proceedings of the XIV Regular Meeting of the Nordic Society for Radiation Protection, NSFS – Rättvik, Sweden, 27–31 August 2005. SSI Report 2005:15. Stockholm: Swedish Radiation Protection Authority; 2005. p. 225–227.

Website links

www.stuk.fi (Radiation and Nuclear Safety Authority – STUK)

www.radon.fi (Link to radon pages at *www.stuk.fi*)

www.ymparisto.fi (The National Building Code of Finland)

www.rakennustieto.fi > Products and services > Information Files (Building Information Ltd.)

3.5 France

Regulations and guidance

Current regulation exists for some public buildings (mainly schools) and some underground activities. Regulations for existing dwellings should be adopted in near future (regulations are in preparation). The current action level for radon remediation is 400 Bq/m^3. For new building, there are plans for setting regulations but these have not been prepared yet.

Guide for remediation and prevention:

- Le radon dans les bâtiments. Guide pour la remédiation dans les constructions existantes et la prévention dans les constructions neuves. Guide technique CSTB, juillet 2008. (In French).

Status of remediation and prevention

Table 11 provides the estimated number of dwellings exceeding the action level. The number of dwellings in which remediation measures have been applied is not known.

Table 11. Status of radon remediation in France.

	In low-rise residential buildings	In apartment buildings
Estimated number of dwellings	18 625 000	14 131 000
Estimated number of dwellings exceeding the action level	968 500	No data
Estimated number of dwellings already remediated	No data	No data

The estimated number of houses where preventive measures have been taken was not reported.

Technologies used for remediation of existing buildings

The remediation methods used in France and the reduction factors of the methods reported in the questionnaire response are given in Table 12. In addition to common methods, reducing under-pressure in the house with insufflating mechanical ventilation was reported. Typical combinations are sealing and living space ventilation, sealing and basement ventilation, and living space and basement ventilation. It should be noted that data in the Table 12 are from French public buildings and not from dwellings.

Table 12. Reduction factors of radon remediation methods reported in the questionnaire by France (data from French public buildings).

Remediation method	Reduction factor (%), typ. range
Sub-slab depressurization	89
Improving natural ventilation in living spaces	49
Improving mechanical ventilation in living spaces	61
Improving cellar ventilation	47
Sealing entry routes	55
Improving crawl space ventilation	47
Reducing under-pressure in the house with insufflating mechanical ventilation	81
Sealing + building ventilation	72
Sealing + basement ventilation	68
Building and basement ventilation	67

Selected list of publications

Collignan B, Millet JR. Estimation of radon concentration in house using a simple ventilation model. In: Radon in the living environment. Athens workshop. 1999 Apr 19–23; Athens, Greece.

Collignan B, O'Kelly P. Dimensioning of soil depressurization system for radon remediation in existing buildings. In: Proceedings of ISIAQ 7th International Conference Healthy Buildings. Vol. 1. 2003 Dec 7–11; Singapore. p. 517–523.

Collignan B, O'Kelly P, Pilch E. Basement depressurisation using dwelling mechanical exhaust ventilation system. In: 4th European Conference on Protection against radon at home and at work. 2004 Jun 28 – Jul 2; Praha.

Collignan B, Abdelouhab M, Allard F. Experimental study on passive sub-slab depressurisation system. In: AARST's 18th International Radon Symposium. 2008 Sep14–17; Las Vegas, USA.

Le radon dans les bâtiments. Guide pour la remédiation dans les constructions existantes et la prévention dans les constructions neuves. Guide technique CSTB, juillet 2008. (In French)

Website links

ese.cstb.fr/radon

3.6 Germany

Regulations and guidance

The action level for radon remediation is 100 Bq/m^3 and the recommended target level in new building is 100 Bq/m^3. It should be noted that the action level is voluntary.

Guide for radon remediation and prevention:

- Radon-Handbuch Deutschland.

Status of remediation and prevention

Table 13 provides the estimated number of dwellings exceeding the voluntary action level and number of dwellings in which remediation measures have been applied.

Table 13. Status of radon remediation in Germany.

	In low-rise residential buildings	In apartment buildings
Estimated number of dwellings	18 300 000	21 600 000
Estimated number of dwellings exceeding the action level	1 930 000	unknown
Estimated number of dwellings already remediated	<1 000 (estim.)	unknown

The estimated number of houses where preventive measures have been taken is approximately 1 000.

Technologies used for remediation of existing buildings

The remediation methods used are sub-slab depressurization, replacing the existing natural room air ventilation with mechanical exhaust ventilation, house pressurization and sealing entry routes.

Technologies used for prevention in new construction

The prevention methods used are passive and active sub-slab depressurization, radon-proof barrier with membrane below or above the floor slab, sealing the joint of floor slab and foundation wall using membranes, sealing the pipe penetrations in structures with soil contact, and use of waterproof concrete instead of normal concrete. An additional method was also reported where double radon-proof membrane above the floor slab is combined with depressurization of the space between the membranes.

Selected list of publications

Radon-Handbuch Deutschland

Website links

www.bfs.de/en/ion/radon

3.7 Greece

Regulations and guidance

The action level for radon remediation is 400 Bq/m^3 and the recommended target level in new building is 200 Bq/m^3. The estimated number of dwellings exceeding the action level and those already remediated as well as the estimated number of houses where preventive measures have been taken were not reported.

Technologies used for remediation of existing buildings

The remediation methods used include sub-slab depressurization, improving natural ventilation in living spaces, improving mechanical ventilation in living spaces, replacing the existing natural room air ventilation with mechanical exhaust ventilation, improving ventilation in cellar and sealing entry routes.

Technologies used for prevention in new construction

The prevention methods used are radon-proof barrier with membrane below or above the floor slab and sealing the joint of floor slab and foundation wall using membranes. In addition, use of waterproof concrete instead of normal concrete has been used.

Selected list of publications

Greek Atomic Energy Commission

General Secretariat of the National Statistical Service of Greece

Technical Chamber of Greece

The radon at primary schools of Lesvos Island. Aegean University.

Clouvas A, Xanthos S, Antonopoulos-Domis M. A combination study of indoor radon and in situ gamma spectroscopy measurements in Greek dwellings. Radiation Protection Dosimetry 2003; 103 (4): 363–366.

Clouvas A, Takoudis G, Xanthos S, Potiriadis C, Kolovou M. Indoor radon measurements in areas of northern Greece with relatively high indoor radon concentrations. Radiation Protection Dosimetry 2009; 136 (2): 127–131.

Commission Recommendation of 21 February 1990 on the protection of the public against indoor exposure to radon. 90/143/Euratom.

Geranios A, Kakoulidou M, Mavroidi Ph, Moschou M, Fischer S, Burian I, Holecek J. Radon survey in Kalamata (Greece). Radiation Protection Dosimetry 2001; 93 (1): 75–79.

Nikolopoulos D, Louizi A, Koukouliou V, Serefoglou A, Georgiou E, Ntalles K, Proukakis Ch. Radon survey in Greece-risk assessment. Journal of Environmental Radioactivity 2002; 63: 173–186.

Papaefthymiou H, Georgiou CD. Indoor radon levels in primary schools of Patras, Greece. Radiation Protection Dosimetry 2007; 124 (2): 172–176.

Website links

www.eeae.gr

3.8 Ireland

Regulations and guidance

The reference level for long-term exposure to radon in both existing and new dwellings in Ireland is 200 Bq/m^3. The radon levels in existing houses have been studied by the Radiological Protection Institute of Ireland (RPII). In 2002 it published the results of a national survey of radon levels in existing houses, Radon in Dwellings – The Irish National Radon Survey. From this survey, it was estimated that some 91 000 houses or 7% of the total housing stock have radon concentrations above the reference level. Based on the results of the survey, the RPII has also identified high radon areas, where more than 10% of dwellings have radon concentrations above 200 Bq/m^3. The number of dwellings already remediated is not known.

Two guides dealing with radon remediation exist in Ireland:

- Radon in existing buildings – Corrective options. Dublin: Department of the environment and local government; 2002.
- Understanding radon remediation – A householder's guide. Radiological Protection Institute of Ireland.

The latter guide is directed at householders who have been informed that they have radon concentrations above the reference level in their home. The aim of the guide is to assist such householders in interpreting their radon measurement results and in deciding how to deal with the problem. The guide provides basic information on radon remediation methods so as to enable householders to decide what to do next. It does not provide detailed technical instructions for radon remediation, but aims to give householders a general understanding of the methods available. Householders who wish to do the work themselves or who require more information should refer to "Radon in existing buildings – Corrective options". This guide is intended to inform designers, contractors, and building owners about radon and the means to deal with high concentrations in existing buildings. It gives some pointers as to good practice insofar as it relates to non-complex buildings of normal design and construction. Reference has been made to the usual ways of minimising radon levels and guidance is given on sources of further information.

Since July 1998, all new dwellings and long-stay buildings have been required to incorporate some degree of radon preventative measures at the time of construction in accordance with the revised Building Regulations (1997, Technical guidance document C). The degree of protection required is dependent upon whether the site is located within a high or low radon area. The publication

“Radon in existing buildings – Corrective options” gives information to building designers and householders about measures they can take to reduce high radon.

Status of remediation and prevention

Table 14 provides the estimated number of dwellings exceeding the action level. The number of dwellings in which remediation measures have been applied is not known, but the number is thought to be low.

There are no accurate data for the number of houses where preventive measures have been taken. However, it was estimated that roughly 700 000 dwellings have been built since 1998, when the law with the new building code including guidelines for radon prevention was enacted.

Table 14. Status of radon remediation in Ireland.

	In low-rise residential buildings	In apartment buildings
Estimated number of dwellings	1 740 600	193 400
Estimated number of dwellings exceeding the action level	91 000 in total. The breakdown between houses and apartments is not known	
Estimated number of dwellings already remediated	Not known, but the number is thought to be low.	

Technologies used for remediation of existing buildings

The most common remediation techniques in the Irish guidance include: sub-floor depressurization (radon sump), increased under-floor ventilation, positive pressurization, increased indoor ventilation, and the sealing of cracks and gaps in the floor and around service entry points. Figure 1 shows a guide to the likely effectiveness of remediation techniques.

Sealing of floors and walls is likely to result in a reduction factor of less than 50%. For this method to be successful, effectively all gaps have to be sealed. Increasing indoor ventilation is possible e.g. by unblocking air vents or by providing additional wall vents. Installing a mechanically balanced supply/exhaust system with heat recovery has many benefits, e.g. a low resulting depressure. However, a reasonably well sealed building is required. Increasing the under-floor ventilation is a technique for houses with a suspended floor. Radon levels up to 850 Bq/m^3 may have an easily remedied situation. Positive pressurization means blowing air into the house from a specially installed fan unit. This reduces under-pressure in living spaces or creates a positive pressure compared to under-floor spaces.

A radon sump has provided the best remediation results. A sump cavity in the under-floor hardcore may be implemented either through the floor slab or the external foundation walls. An excavated sump is likely to have an influence over an area of at least 250 m^2, but obstruction below the floor slab may reduce the effectiveness. A passive system involving a sump and pipe work system taken up through the building may also be sufficient to reduce the under-floor pressure. Such a system uses the wind and stack effect and it has been successfully used even for levels in excess of 800 Bq/m^3.

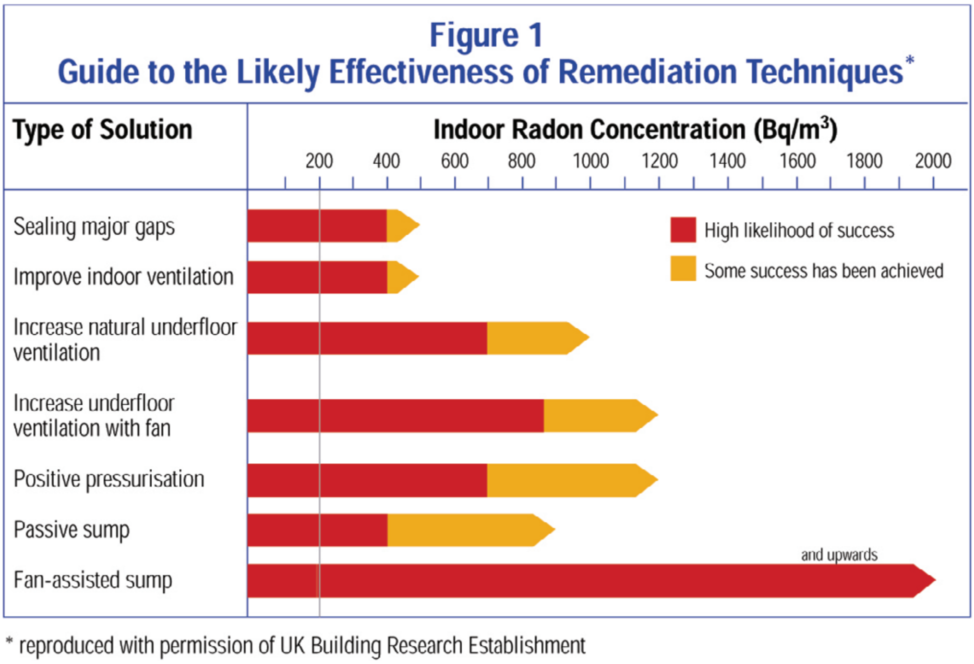

Figure 1. Likely effectiveness of remediation techniques (From the Irish guide: Understanding radon remediation, A householder's guide).

Effectiveness of radon remediation in Irish Schools

A national survey of radon in Irish schools was carried out on a phased basis from 1998 to 2004. Measurements were completed in 38 531 ground floor classrooms and offices in 3 826 schools, representing over 95% of the approximately 4 000 primary and post-primary schools in Ireland. Of these, 984 schools had radon concentrations greater than 200 Bq/m^3 in 3 028 rooms, and 329 schools had radon concentrations in excess of 400 Bq/m^3 in 800 rooms.

Synnott et al. (2007) reported on the effectiveness of the radon remediation solutions used in schools. Active systems such as sumps and fan assisted under-floor ventilation were generally applied in class rooms with radon concentrations above 400 Bq/m^3. These proved effective with average radon reduction factors[1] of 9 to 34 (reduction of 89–97%) being achieved for radon sumps and 13 to 57 (92–98%) for fan assisted under-floor ventilation (see Table 15). Both techniques achieved maximum radon reduction factors in excess of 100 (99%).

Passive systems such as wall and window vents were used to increase the background ventilation in rooms with radon concentrations below 400 Bq/m^3, and achieved radon reductions of approximately 55%.

Technologies used for prevention in new construction

In the high radon areas, measures should be taken to protect the building from radon in the ground. For example, in the case of a non-complex building of normal design and construction, a fully sealed membrane of low permeability over the entire footprint of the building and a potential means of extracting radon from the substructure such as a standby radon sump or sumps with connecting pipework or other appropriate certified systems should be provided.

In other areas, the building should be provided with a potential means for extracting radon from the substructure if this proves necessary after construction. For example, in the case of a non-complex building of normal design and construction, the provision of a standby radon sump or sumps with connecting pipework or other appropriate certified systems should be adequate.

Table 15. The effectiveness of different radon remediation methods in Irish schools (Synnott et al. 2007).

	Radon concentration from original survey (Bq m^{-3})														
	200–400					400–1 000					>1 000				
		Reduction factor					Reduction factor					Reduction factor			
System type	*N*	Arith mean	Min	Max	Geom mean	*N*	Arith mean	Min	Max	Geom mean	*N*	Arith mean	Min	Max	Geom mean
Radon sump	89	9	1.2	33	7.4	180	16	1.4	81	12	61	34	1.6	172	23
Radon sump with other methods	15	6.2	2.0	12	5.3	6	11	2.3	25	8.4	1	–	–	20	–
Active under-floor ventilation	4	13	1.5	27	7.8	6	32	12	49	29	4	57	29	129	46
Active under-floor ventilation with other methods	0	–	–	–	–	3	20	1.8	45	10	6	64	2.8	141	31
Increased back-ground ventilation	175	2.3	0.7	9.1	2.1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

1 Synnot et al. (2007) have calculated the reduction factor as the ratio of the radon concentration before and after remediation.

Selected list of publications

Action plan to identify and remedy Irish houses with radon concentrations above the national Reference Level. Radiological Protection Institute of Ireland; 2006.

Organo C, Ellard A, Fenton D, Synnott H, O'Colmáin M, Prenter S, O'Reilly S, Colgan PA. High radon concentrations in a house near Castleisland, County Kerry (Ireland) – identification, remediation and post-remediation. Journal of Radiological Protection 2004; 24 (2): 107–120.

Radon in existing buildings, Corrective options. Dublin: Department of the environment and local government; 2002.

Synnott H, Colgan PA, Hanley O, Fenton D. The effectiveness of radon remediation in Irish schools. Health Physics 2007; 92 (1): 50–57.

Understanding radon remediation, A householder's guide. Radiological Protection Institute of Ireland.

Website links

www.environ.ie/en/Environment/EnvironmentalRadiation/Radon/,
The Department of the Environment, Heritage and Local Government
www.rpii.ie/, The Radiological Protection Institute of Ireland

3.9 Italy

Regulations and guidance

In Italy there is presently no action level for existing dwellings or target level for new buildings.

However, the Scientific Committee of the Italian National Radon Programme recommended in 2009 that preventive measures against radon should be required for every new building. In some regions or municipalities, some preventive measures are already required for new buildings, generally referring to the above recommendation.

The following guides exist for radon remediation and for prevention:

- Minach L, Giovani C, Garavaglia M. Linee guida relative ad alcune tipologie di azioni di risanamento per la riduzione del radon (Guidelines referring to some remediation methods for radon reduction in buildings). APAT –RTI CTN_AGF 4/2005.
- Linee Guida su azioni preventive nei nuovi edifici (Guidelines for radon prevention in new buildings). (In Italian)

Status of remediation and prevention

Table 16 provides the estimated number of dwellings exceeding 200 Bq/m^3 and the number of dwellings in which remediation measures have been applied. In the master questionnaire, it was reported that in 4.1% of the dwellings the radon concentration is above 200 Bq/m^3 and that more than 450 dwellings have been remediated.

Table 16. Status of radon remediation in Italy.

	In low-rise residential buildings	In apartment buildings
Estimated number of dwellings	22 000 000	
Estimated number of dwellings exceeding the action levels	902 000	
Estimated number of dwellings already remediated	450	

The number of houses where preventive measures have been taken is not known.

Technologies used for remediation of existing buildings

The remediation methods used in Italy are sub-slab depressurization, improving mechanical ventilation in living spaces (taking care to avoid depressurization in the room), installation of a new mechanical supply and exhaust ventilation system with heat recovery, improving ventilation in the crawl space or in the cellar, and constructing a radon well. House pressurization has rarely been used, and for single rooms only. Reducing under-pressure in the house (avoiding an extractor fan) and sealing entry routes have only been used in combination with other methods. In addition, adding a new floor upon the existing one with a cavity below has been used, especially in the case of renovations. A typical combination is the sealing of entry routes and sub-slab depressurization.

The reduction factors of the remediation methods reported in the questionnaire response are given in Table 17.

Table 17. Reduction factors of radon remediation methods reported in the questionnaire by Italy.

Remediation method	Reduction factor (%), typ. range
Sub-slab depressurization	60 – 95
Improving mechanical ventilation in living spaces	20 – 95
House pressurization (higher pressure indoors than in the soil under the floor)	60 – 95
Improving cellar ventilation	60 – 90
Improving crawl space ventilation	60 – 90

Technologies used for prevention in new construction

The prevention methods used are passive and active sub-slab depressurization, radon-proof barrier with a membrane below or above the floor slab, sealing of the joint between the floor slab and foundation wall using membranes, sealing of pipe penetrations in structures in contact with soil and the use of waterproof concrete instead of normal concrete. All these methods are recommended by some regional Environmental Protection Agencies; however, there is no register (at present) containing information on which methods have actually been applied.

Selected list of publications

ARPAV. Sperimentazione delle azioni di rimedio sugli edifici con alta concentrazione di gas radon nel Veneto. 2007. (In Italian, available at *www.arpa.veneto.it/agenti_fisici/docs/radon/Rapportobonifiche2007.pdf*) *This is a research report by the Environmental Protection Agency of the Veneto Region. It contains the description of radon mitigation methods and some experimental results of the efficiency of radon reduction for a group of houses with high radon concentration*

Bertagnin M, Garavaglia M, Giovani C, Russo G, Villalta R. 2003 – Indicazioni e proposte per la protezione degli edifici dal radon – ARPA Friuli Venezia Giulia, 32 pages. (In Italian, available at *www.arpa.fvg.it/fileadmin/Informazione/Pubblicazioni/pubbl_radiazioni/radon-IndicazioniProtezioneEdifici.zip*).

This is a comprehensive brochure by the Environmental Protection Agency of the Friuli-Venezia Giulia Region

Linee Guida su azioni preventive nei nuovi edifici (Guidelines for radon prevention in new buildings). (In Italian)

This document has been produced in the framework of the Italian National Radon Programme and it is going to be published.

Minach L, Giovani C, Garavaglia M. Linee guida relative ad alcune tipologie di azioni di risanamento per la riduzione del radon (Guidelines referring to some remediation methods for radon reduction in buildings). APAT –RTI CTN_AGF 4/2005. (In Italian, available at *www.arpa.umbria.it/au/sinanet/Radiazioni%20Ionizzanti/IR_04/AGF-T-LGU-04-03.pdf*)

Torri G, Feroce C, Giangrasso M, Notaro M. Remedial action in buildings with high radon concentrations – applications in a few Italian dwellings. Radiation Protection Dosimetry 1998; 78 (1): 45–48.

Website links

www.provincia.bz.it/agenzia-ambiente/radiazioni/contromisure.asp

Link to the webpage (in Italian and German) of the “Provincia Autonoma di Bolzano” that describes the remediation methods used by the local Environmental Agency. This page contains links to other relevant documents and websites).

3.10 Norway

Regulations and guidance

For radon remediation, there are two limits: the recommended action level is 100 Bq/m^3, and the recommended maximum level is 200 Bq/m^3. The recommended target level in new buildings is 100 Bq/m^3. For new housing, these limits are under review to become legally binding.

The following guides exist for radon remediation:

- Byggforsk: Tiltak mot radon I eksisterende bygninger. Byggforskserien, Byggforvaltning 701.706, Sending 1 – 2006,
- Statens bygningstekniske etat: Radon, temaveiledning. Melding HO-3/2001, BE, NRPA, Norges byggforskningsinstitutt, and for prevention
- Byggforsk: Sikring mot radon ved nybygging. Byggdetaljer 2–2006.

Status of remediation and prevention

Table 18 provides the estimated number of dwellings exceeding the action level. The number of dwellings in which remediation measures have been applied is not known.

Table 18. Status of radon remediation in Norway.

	In low-rise residential buildings	In apartment buildings
Estimated number of dwellings	1 779 689	494 673
Estimated number of dwellings exceeding the action levels	147 663 over 200 Bq/m^3 387 600 over 100 Bq/m^3	14 840 over 200 Bq/m^3 39 375 over 100 Bq/m^3
Estimated number of dwellings already remediated	?	?

The estimated number of houses where preventive measures have been taken was not reported.

Technologies used for remediation of existing buildings

The remediation methods used in Norway and the reduction factors of the methods reported in the questionnaire response are given in Table 19. In addition to common methods, soil ventilation by exhaust air from the house was reported in the questionnaire. This method has also been used in Sweden. A typical combination is sealing of entry routes and improving natural ventilation. In addition, it was stated that all methods should be applied in combination with sealing of entry routes.

Table 19. Reduction factors of radon remediation methods reported in the questionnaire by Norway.

Remediation method	Reduction factor (%), typ. range
Sub-slab depressurization	50–95
Improving natural ventilation in living spaces	10–50
Improving mechanical ventilation in living spaces	10–20
Replacing the existing natural room air ventilation with mechanical exhaust ventilation	10–20
Installation of a new mechanical supply and exhaust ventilation system with heat recovery	10–80
Improving cellar ventilation	10–50
Reducing under-pressure in the house	10–50
Sealing entry routes	10–60
Improving crawl space ventilation	10–80
Soil ventilation by exhaust air from house	50–95
Sealing entry routes + improving natural ventilation	20–80

Technologies used for prevention in new construction

The prevention methods used and the reduction factors of the methods reported in the questionnaire response are given in Table 20. In addition to common methods, a preparatory arrangement for sub-slab or crawl space ventilation with exhaust air from the house was reported. This normally utilizes a cast-in sump, which also applies for active SSD.

Table 20. Reduction factors of radon prevention methods reported in the questionnaire by Norway.

Prevention method	Reduction factor (%), typ. range
Passive sub-slab depressurization	0–20
Active sub-slab depressurization	70–95*
Radon-proof barrier, membrane above floor slab	0–90
Sealing the joint between floor slab and foundation wall with membranes	0–90
Sealing pipe penetrations in structures with soil contact	0–90
Arrangement for sub-slab or crawl space ventilation with exhaust air from house	70–95*

* Normally this is only arranged for by a cast-in sump.

Selected list of publications

Byggforsk. Tiltak mot radon I eksisterende bygninger. Byggforskserien, Byggforvaltning 701.706, Sending 1 – 2006.

Byggforsk. Sikring mot radon ved nybygging. Byggdetaljer 2–2006.

Jelle BP, Noreng K, Erichsen TH, Strand T. Implementation of radon barriers, model development and calculation of radon concentration in indoor air. Journal of Building Physics 2011; 34: 195–222.

Statens bygningstekniske etat. Radon, temaveiledning. Melding HO-3/2001, BE, NRPA, Norges byggforskningsinstitutt; 2001.

Sundal AV, Henriksen H, Soldal O, Strand T. The influence of geological factors on indoor radon concentrations in Norway. Science of the Total Environment 2004; 328 (1–3): 41–53.

Sundal AV, Jensen CL, Ånestad K, Strand T. Anomalously high radon concentrations in dwellings located on permeable glacial sediments. Journal of Radiological Protection 2007; 27 (3): 287–298.

Sundal AV, Valen V, Soldal O, Strand T. The influence of meteorological parameters on soil radon levels in permeable glacial sediments. Science of The Total Environment 2008; 389 (2–3): 418–428.

Website links

www.nrpa.no/ > radon

3.11 Portugal

Regulations and guidance

The action level for radon remediation is 400 Bq/m^3. The recommended target level in new buildings is 400 Bq/m^3. This is applied only for large buildings.

Status of remediation and prevention

It has been estimated that 2.6% of the dwellings exceed the action level. The number of dwellings already remediated is not known. In new buildings, preventive measures have only been taken in a few cases.

Technologies used for remediation of existing buildings

The remediation methods used include improving natural ventilation in living spaces, improving mechanical ventilation in living spaces, replacing the existing natural room air ventilation with mechanical exhaust ventilation and sealing entry routes. Other methods were also reported: a radon gas barrier and building a crawl space.

The reduction factors of the remediation methods reported in the questionnaire response are given in Table 21.

Table 21. Reduction factors of radon remediation methods reported in the questionnaire by Portugal.

Remediation method	Reduction factor (%), typ. range
Radon-gas barrier	40 – 70
Building of crawl space	60 – 80

Technologies used for prevention in new construction

The prevention methods reported are passive and active SSD, and radon-proof barrier with a membrane above the floor slab. In addition, building a crawl space and detailed radon risk maps were reported in the questionnaire response.

The reduction factors of the prevention methods reported in the questionnaire response are given in Table 22.

Table 22. Reduction factors of radon prevention methods reported in the questionnaire by Portugal.

Prevention method	Reduction factor (%), typ. range
Passive sub-slab depressurization	20 – 50
Active sub-slab depressurization	40 – 70
Radon-proof barrier, membrane above floor slab	30 – 60
Building a crawl space	70 – 90

Selected list of publications

Colgan PA, Gutierrez J. National approaches to controlling exposure to radon. Environment International 1996; 22 (Supplement 1): 1083 – 1092.

Dubois G. An overview of radon surveys in Europe. Luxembourg: Office for Official Publications of the European Communities; 2005. EUR 21892 EN.

Faisca MC, Teixeira MMGR, Bettencourt AO. Indoor radon concentrations in Portugal – a national survey. Radiation Protection Dosimetry 1992; 45: 465 – 467.

Oliveira Fernandes E, Jantunen M, Carrer P, Seppänen O, Harrison P, Kephalopoulos S. Publishable final report: Policies on indoor air quality: assessment and needs. ENVIE Project. European Commission 6th Framework Programme of Research. Brussels; 2008.

Website links

www.dct.uc.pt/lrn

3.12 Spain

Regulations and guidance

In Spain, there are no reference levels or guides for radon remediation and prevention. Hence, no remedial or preventive actions for general population have been done. However, research activities in a pilot house have been carried out by the University of Cantabria (Vázquez et al. 2011).

The first national survey of indoor radon in Spain was carried out in 1988–1989 (Quindós et al. 1991). The indoor radon concentration was measured in 1 555 houses. The houses were selected based on population-weighted random sampling, also taking into account the different geological areas of the country. The geometric mean was 41 Bq/m^3 and highest value found was 15 400 Bq/m^3. In about 4% of houses, the radon concentration was higher than 400 Bq/m^3. More surveys have subsequently been carried out (5 400 houses measured), in which the geometric mean of 45 Bq/m^3 has been estimated for the whole country and 130 Bq/m^3 in the high radon areas (Quindós Poncela et al. 2004).

Selected list of publications

Baixeras C, Font Ll, Robles B, Gutiérrez J. Indoor radon survey in the most populated areas in Spain. Environment International 1996; 22: 671–676.

Quindós LS, Fernández PL, Soto J. National survey on indoor radon in Spain. Environment International 1991; 17: 449–453.

Quindós LS, Fernández PL, Soto J, Madrid J. Radon and lung cancer in Spain. Radiation Protection Dosimetry 1991; 36: 331–333.

Quindós LS, Soto J, Fernández PL. Study of areas of Spain with high indoor radon. Radiation Measurements 1995; 34 (2): 207–210.

Quindós Poncela LS, Fernández PL, Gómez Arozamena J, Sainz C, Fernández JA, Suarez Mahou E, Martin Matarranz JL, Cascón MC. Natural gamma radiation map (MARNA) and indoor radon levels in Spain. Environment International 2004; 29 (8): 1091–1096.

Vázquez BF, Adán MO, Quindós Poncela LS, Fernandez CS, Merino IF. Experimental study of effectiveness of four radon mitigation solutions, based on underground depressurization, tested in prototype housing built in a high radon area in Spain. Journal of Environmental Radioactivity 2011; 102 (4): 378–385.

Website links

www.elradon.com: this webpage includes a great deal of information on radon (in Spanish).

3.13 Switzerland

Regulations and guidance

The action level for radon remediation is 1 000 Bq/m^3 for dwellings and 3 000 Bq/m^3 for working places. There is a guideline value of 400 Bq/m^3 for existing buildings after mitigation and for new buildings.

The following guide exists for radon remediation and prevention:

- Swiss radon handbook. Swiss Federal Office of Public Health; 2000. (In French, German, Italian, English)

Status of remediation and prevention

Table 23 provides the estimated number of dwellings exceeding the action level and the number of dwellings in which remediation measures have been applied.

Table 23. Status of radon remediation in Switzerland.

	In low-rise residential buildings	In apartment buildings
Estimated number of dwellings	Total: ~4 000 000 dwellings – low-rise: ~30% – apartments: ~70%	
Estimated number of dwellings exceeding the limit value	5 000 – 10 000 (2 800 already found, August 2010)	
Estimated number of dwellings exceeding the guideline value	50 000 – 100 000 (11 000 already found, August 2010; this number includes dwellings over the limit value)	
Estimated number of dwellings already remediated	~ 500	

The number of houses where preventive measures have been taken was estimated to be less than 5 000.

Technologies used for remediation of existing buildings

The remediation methods used are sub-slab depressurization, improving natural ventilation in living spaces, improving mechanical ventilation in living spaces, replacing the existing natural room air ventilation with mechanical exhaust ventilation, installation of a new mechanical supply and exhaust ventilation system with heat recovery, house pressurization, improving cellar ventilation, reducing under-pressure in the house, sealing entry routes and improving crawl space ventilation. Other methods used are soil ventilation through existing drainage piping outside the footings and radon wells.

The reduction factors of the remediation methods reported in the questionnaire response are given in Table 24.

Table 24. Reduction factors of radon remediation methods reported in the questionnaire by Switzerland.

Remediation method	Reduction factor (%), typ. range
Sub-slab depressurization	90
Improving cellar ventilation	75
Reducing under-pressure in the house	25
Sealing entry routes	25
Improving crawl space ventilation	75
Radon well (soil ventilation, outside the house)	90
Soil ventilation through existing drainage piping outside the footings	50

Technologies used for prevention in new construction

The prevention methods used and the reduction factors of the prevention methods reported in the questionnaire response are given in Table 25.

Table 25. Reduction factors of radon prevention methods reported in the questionnaire by Switzerland.

Prevention method	Reduction factor (%), typ. range
Passive sub-slab depressurization	50
Active sub-slab depressurization	95
Radon-proof barrier, membrane below floor slab	50
Radon-proof barrier, membrane above floor slab	50
Sealing the joint between floor slab and foundation wall with membranes	30
Sealing pipe penetrations in structures with soil contact	50

Selected list of publications

Swiss radon handbook. Swiss Federal Office of Public Health; 2000. (In French, German, Italian, English)

Website links

www.ch-radon.ch (in French, German, Italian, English)

- "Recommendations for the radon risk level (in French)" (in the menu on the right side)
- Section "documentation" in the menu on the right side:
    - Swiss radon handbook (in French, German, Italian, English)
    - Information booklets (in French, German and Italian)

- Section “documentation” in the menu on the right, click on “legal foundations” on right:
    - Ordinance on radiation protection (in French, German, Italian, English)

www.worldradonsolutions.info/, World radon solutions database

3.14 United Kingdom

Regulations and guidance

The action level for radon remediation is 200 Bq/m^3 and the recommended target level in new buildings is 200 Bq/m^3.

Several guides for mitigation have been published by BRE, UK. The following guides were reported in the questionnaire:

- Radon sump systems: BRE guide to radon remedial measures in existing dwellings. BRE report BR227. Authors: C Scivyer, A Cripps and MPR Jaggs. 1998
- BRE Guide to radon remedial measures in existing dwellings. Dwellings with cellars and basements. BRE report 343, 1998
- Sealing cracks in solid floors: a BRE guide to radon remedial measures in existing dwellings. BRE Report 239, 1993
- Positive pressurisation: BRE guide to radon remedial measures in existing dwellings. BRE report BR281, 1995

Guides for radon prevention in new buildings:

- Radon: protective measures for new buildings. BRE report BR211, 2007.

Status of remediation and prevention

Table 26 provides the estimated number of dwellings exceeding the action level and number of dwellings in which remediation measures have been applied.

Table 26. Status of radon remediation in the UK.

	In low-rise residential buildings	In apartment buildings
Estimated number of dwellings	23 000 000	
Estimated number of dwellings exceeding the action level	100 000	
Estimated number of dwellings already remediated	15 000	

The number of houses where preventive measures have been taken is not known. However, it could be quite a large number, because the guidelines for radon prevention in new construction have already existed since 1991.

Technologies used for remediation of existing buildings

The best solution for a particular house depends on the type of house and the amount of radon reduction that needs to be achieved. The options are to install a radon sump system, to improve ventilation under suspended timber floors, to use positive pressurisation and ventilation in the house, to seal cracks and gaps in solid concrete floors, and to change the way the house is ventilated. The most effective (and usually most expensive) option heads the list; the other options vary in cost according to individual house needs, so they cannot be put in a strict order. If the indoor radon level is not very far above the action level, one of the simpler options may be adequate.

The reduction factors of the remediation methods reported in the questionnaire response are given in Table 27. They agree with the new data (Hodgson et al. 2011).

Table 27. Reduction factors of radon remediation methods reported in the questionnaire by UK. The percentage reductions are geometric means of homes measured.

Remediation method	Reduction factor (%), typ. range
Sub-slab depressurization	89
Improving natural ventilation in living spaces	33
Reducing under-pressure in the house	60
Sealing entry routes	41
Improving crawl space ventilation	47
Mechanical ventilation of underfloor space	64

Technologies used for prevention in new construction

The BRE guide on Radon, Guidance on protective measures for new buildings includes the following aspects concerning radon prevention. There are two main principles for providing radon protection in new buildings. The first is to provide a barrier to radon. This can be usually achieved by increasing the general air-tightness of the damp protection used in floors and walls. The second one involves providing natural under-floor ventilation, or provision for future mechanical under-floor ventilation, or a powered radon extraction system.

In areas with a significant radon potential, sufficient protection will be provided by a well installed damp-proof membrane modified and extended to form a radon-proof barrier across the ground floor of the building. This gas-tight barrier is known as basic radon protection. New buildings in areas with a higher radon potential should incorporate full radon protection comprising a radon-proof barrier across the ground floor supplemented by provision for sub-floor depressurization or ventilation (either a radon sump or a ventilated sub-floor void). If the radon concentration exceeds the action level, a fan can be installed afterwards.

The reduction factors of the prevention methods reported in the questionnaire response are given in Table 28.

Table 28. Reduction factors of radon prevention methods reported in the questionnaire by UK. The percentage reductions are geometric means of homes measured in a field study (Woolliscroft 1992).

Prevention method	Reduction factor (%), typ. range
Radon-proof barrier, membrane above floor slab	50
Passive ventilation under suspended concrete floor	50

Selected list of publications

BRE report BR211. Radon: protective measures for new buildings. 2007.

BRE report BR227. Radon sump systems: BRE guide to radon remedial measures in existing dwellings. Authors: Scivyer C, Cripps A, Jaggs MPR. 1998.

BRE Report 239. Sealing cracks in solid floors: a BRE guide to radon remedial measures in existing dwellings. 1993.

BRE report BR281. Positive pressurisation: BRE guide to radon remedial measures in existing dwellings. 1995.

BRE report 343. BRE Guide to radon remedial measures in existing dwellings. Dwellings with cellars and basements. 1998.

Hodgson SA, Zhang W, Bradley EJ, Green BMR, McColl NP. An analysis of radon remediation methods. HPA-CRCE-019. Oxfordshire, UK: Health Protection Agency; 2011.

Naismith SP, Miles JCH, Scivyer CR. The influence of house characteristics on the effectiveness of radon remedial measures. Health Physics 1998; 75: 410–416.

Woolliscroft M. The principles of radon remediation and protection in UK dwellings. Radiation Protection Dosimetry 1992; 42 (3): 211–216.

Website links

www.hpa.org.uk/ > Topics > Radon

www.bre.co.uk/radon/

www.ukradon.org/

3.15 Summary of national situation

The characteristics of radon control in each country are presented in Table 29. The number of dwellings exceeding the national action level of 400 Bq/m^3 varies between 0.4 and 2.6% of the total number of dwellings. In countries where a lower action level than 400 Bq/m^3 applies, greater percentages are also found, except in the UK. The greatest number of dwellings remediated was reported by the UK, where 15 000 dwellings have already been remediated. The greatest number of houses with preventive measures was reported by Ireland, but this is the number of dwellings built since 1998, when a law was enacted with a new building code including guidelines for radon prevention. In the UK, guidelines for radon prevention in new construction have existed since 1991, but the number of buildings protected is not known.

Table 29. National situation of radon control: the action and target levels for remediation in existing and for prevention in new buildings; the total number of dwellings N_t in both low-rise residential and apartment buildings; the number of dwellings exceeding the action level N_e; the number of dwellings already remediated N_r; and the number of houses with preventive measures.

Country	Action / Target level	Number of all dwellings			
		Total number, N_t	Exceeding, N_e (N_e/N_t)	Remediated, N_r (N_r/N_e)	Preventive measures
Austria	400 / 200	3 700 000	89 000 (2.4%)	25 (0%)	15 (0%)
Belgium	400 / 200	5 043 000	20 000 (0.4%)	1 000 (5%)	?
Czech Republic	400 / 200	3 900 000	76 000 (1.9%)	4 000 (5.3%)	210 000 (5.4%)
Finland	400 / 200	2 450 000	59 000 (2.4%)	4 500 (7.6%)	60 000 (2.4%)
France[1]	400 / –	32 756 000	968 500 (3%)		
Germany[2]	100 / 100	39 900 000	1 930 000 (4.8%)	1 000 (0.1%)	1 000 (0%)
Greece	400 / 200	5 627 500			
Ireland	200 / 200	1 934 000	91 000 (4.7%)		699 000 (36.1%)
Italy[3]	200 / 200	22 000 000	902 000 (4.1%)	500 (0.1%)	
Norway[4], 100	100 / 100	2 274 400	427 000 (18.8%)		
Norway, 200	200 / 100	2 274 400	162 500 (7.1%)		
Portugal	400 / 400		2.6%		few
Spain	– / –				
Switzerland, 1 000	1 000 / 400	4 000 000	7 500 (0.2%)	500 (6.7%)	5 000 (0.1%)
Switzerland[5], 400	400 / 400	4 000 000	75 000 (1.9%)	500 (0.7%)	
UK	200 / 200	23 000 000	100 000 (0.4%)	15 000 (15%)	

[1] FRA: regulations only for public buildings, regulations for existing dwellings in preparation
[2] GER: voluntary action and target level of 100
[3] ITA: no officieal value, recommendation 200
[4] NOR: action limit 100, maximum limit 200
[5] CH: 1 000 limit value, 400 guideline value for existing buildings after mitigation and for new construction

4 Remediation methods

The inflow of radon-laden soil air is the main cause of increasing radon concentrations in indoor spaces. This inflow is forced by under-pressure in rooms above the floor construction compared with soil or spaces beneath the floor. The under-pressure is created by the indoor–outdoor temperature difference, wind and, when in use, also by mechanical ventilation. Typical entry routes include floor-wall joints, cracks in concrete slabs and loose fitting pipe penetrations.

In living spaces, building materials are normally only in special cases the reason for an elevated indoor radon concentration above 200 Bq/m^3. If the air exchange rate is well below the recommended value (e.g., 0.5 1/h), even normal radon emissions can cause elevated indoor radon concentrations.

The methods of indoor radon remediation are normally based on the following principles: depressurization of the soil under floor construction and reduction of the soil air radon concentration, sealing of entry routes, improvement of the air exchange rate and/or reduction of the under-pressure level in living spaces, and a combination of these methods. In this section, these and other remediation methods are discussed, including estimates of the typical radon concentration reduction factors and potential impact on energy consumption based on the questionnaire responses.

4.1 Sub-slab depressurization

A sub-slab depressurization (SSD) system is one of the most efficient and common methods to reduce the radon concentration in indoor air. A basic SSD system, illustrated in Figure 2, consists of a sump, an exhaust pipe and a fan. The sump is excavated under the floor slab and it is filled with coarse gravel. The fan is used to draw radon-laden air from the sub-slab ground through the exhaust duct. This affects indoor radon levels in two ways: it dilutes the radon concentration under the slab and creates a negative pressure difference under the slab compared to the dwelling, which reduces air flow from sub-slab soil into the house.

Numerous variations of the SSD exist, depending on foundation type and practical possibilities for installing a radon sump and exhaust pipework. The sump can be excavated through the slab or through the foundation wall. In the case of walls dividing the foundation into separate blocks, more than one sump may be needed. Perforated pipes implemented through the foundation wall or from cellar can also be used (see Figure 2 and Figure 3). Radon piping (i.e., a network of flexible perforated pipes placed in a sub-floor layer of coarse gravel) has also been used when radon remediation takes place in connection with floor reconstruction.

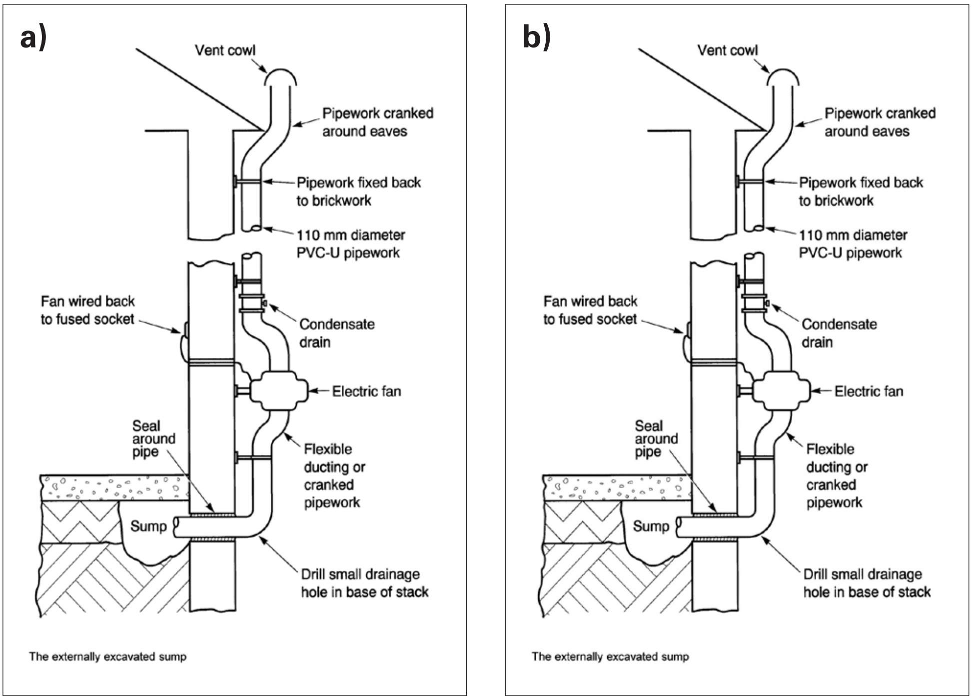

Figure 2. Illustration of a sub-slab depressurization systems in the UK BRE guide (BRE 2003): **a)** Internal mini sump system and **b)** Externally excavated sump system. A roof exhaust fan draws radon-rich air from a sump and sub-slab soil through a vertical exhaust flue.

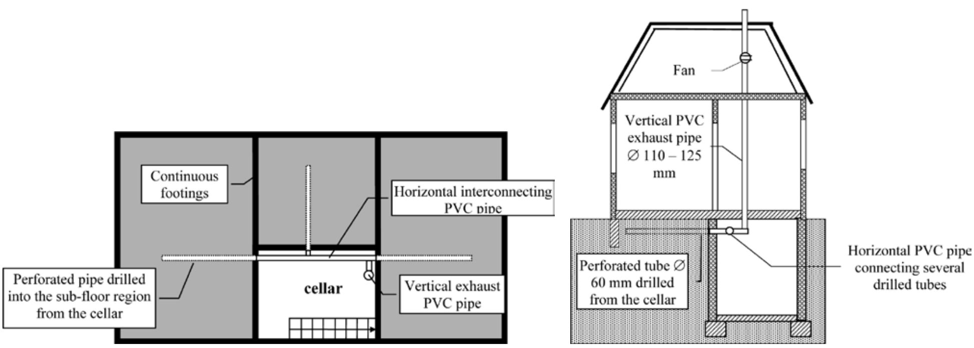

Figure 3. Sub-slab depressurization with perforated pipes drilled through the basement wall (Jiránek 2003).

In the SSD systems illustrated above, a fan is used to draw air from the sub-slab soil. In such a case, it is referred to as active SSD. Nevertheless, SSD can also be a passive system, where the exhaust pipe is led to the open air on the roof without a fan. However, the efficiency of the passive SSD is lower than that of the active SSD.

Efficiency

The percentage reduction of the radon concentration achieved with an SSD is typically 70–95% according the RADPAR WP6 Questionnaire. Efficiencies reported by different countries are listed in Table 30.

Table 30. Typical range of reduction factors in different countries for sub-slab depressurization.

Country	Reduction factor (%), Typ. range
Austria	80
Belgium	90
Czech Republic	85–95
Finland	65–95
France	89
Italy	60–95
Norway	50–95
Switzerland	90
United Kingdom	89

The efficiency of SSD systems depends on the permeability of the soil under the slab. The efficiency is reduced if the soil under the foundations is not permeable enough. On the other hand, the efficiency can also be lower if the house is built on highly permeable soil. In this case, the under-pressure is not well developed, since the SSD draws too much air directly from outside the foundation.

Impact on energy consumption

The impact of sub-slab depressurization on energy consumption is small in most cases. Some minor negative effects may appear in cold climates (i.e., floor can be cooled), if large amounts of air are drawn from sub-slab soil, or if the floor is not adequately insulated. On the other hand, sub-slab soil can be warmed up in summer. In Finland, for example, there is guidance on the air flow drawn from the sub-slab space. The air flow should not be more than 0.2-0.5 m^3/h per m^2 of slab, although this reference value is sometimes exceeded. Nevertheless, the energy consumption is increased at least somewhat due to the electrical power required by the fan. The typical fan power is 50–70 W. For example, the use of a 70 W fan 24 hours per day for six months amounts to approximately 300 kWh.

4.2 Building ventilation

Improving ventilation in living spaces

Improving ventilation in living spaces may include various measures. Sometimes, simply opening fresh air vents is adequate for lowering the radon levels. This measure increases the ventilation and also reduces the under-pressure of the dwelling. Improving natural ventilation may include, in addition to previous measure, adding fresh air vents, or opening more or adding exhaust vents.

Improving mechanical exhaust ventilation may include opening the fresh air vents, adding fresh air vents or increasing the exhaust air flow. The efficiency of this method varies considerably depending on the actions carried out: opening and adding fresh air vents increases the air exchange rate and also reduces under-pressure. This reduces radon entry, and the indoor radon concentration consequently decreases. However, increasing the exhaust air flow of mechanical exhaust ventilation may also have negative effects: despite the increased air exchange, the radon concentration may even rise due to increased under-pressure, which increases the entry of radon-laden air from sub-slab soil. Nevertheless, with a mechanical supply and exhaust ventilation, the air exchange rate can be increased in a controlled way without increasing the under-pressure.

Table 31 presents the reported efficiencies of remediation methods related to improving ventilation in living spaces. In general, the efficiency is typically below 70%. For improved natural ventilation in living spaces, the efficiency is typically 10–50%. The efficiency of the method "Improving mechanical ventilation" is typically 10–60%. However, France reported an efficiency of 61% and Norway only 10–20%. For the efficiency of the method "Replacing the existing natural room air ventilation with mechanical exhaust ventilation", Finland and Norway reported slightly different efficiencies: 15–45% and 10–20%, respectively. The typical range of reduction factors for the method "Installation of new mechanical supply and exhaust ventilation system with heat recovery" is about 30–60%. Norway reported a larger range (10–80%). In many cases, for indoor ventilation methods to be effective, the initial ventilation rate should be low.

In general, the energy consumption is proportional to the ventilation rate. Hence, by increasing the air exchange rate the energy consumption is also increased. However, if the initial air exchange rate is low, which is often the condition for the efficiency of the method, the ventilation rate should be increased to ensure the quality of the indoor air. The ventilation rate of 0.5 air changes per hour (ACH) is a typical recommendation in Nordic countries.

The installation of a new mechanical supply and exhaust ventilation system with heat recovery reduces the energy consumption compared to other ventilation schemes.

Table 31. Reduction factor reported by different countries.

	Reduction factor (%), Typ. range						
	AT	CZ	FI	FR	IT	NO	UK
Improving natural ventilation in living spaces		<30	15–55	49		10–50	33
Improving mechanical ventilation in living spaces			5–55	61	20–95	10–20	–
Replacing the existing natural room air ventilation with mechanical exhaust ventilation			15–45			10–20	
Installation of a new mechanical supply and exhaust ventilation system with heat recovery	60	30–60	30–65			10–80	

House pressurization

The principle of this remediation method is to create a slight overpressure in the dwelling compared to the sub-slab soil using a ventilation unit with a fan. The overpressure eliminates the indoor under-pressure, which reduces the radon entry rate from the soil into the house. At the same time, the air exchange rate increases, and the radon concentration therefore also decreases by dilution. To ensure the efficiency of this system, the building must be relatively airtight.

Based on the questionnaire, this remediation method is used in some European countries: Austria, the Czech Republic, Germany, Ireland and the United Kingdom. However, in some countries (e.g., Finland and Norway), house pressurization is not allowed or not recommended due to the risk of moisture problems. Such problems may arise in cold climates when warm indoor air encounters cold structures in the house envelope, causing the relative humidity of the air to increase and even condensation to form.

The efficiency of the method is typically 40–80%. Austria reported the typical range of the reduction factor to be 80%. In the literature, geometric means of 47% and 73% have been reported in UK (Naismith 1998) and 40–80% from a summary of Czech standards (Jiránek 2003).

Potential impact on the energy consumption depends on the tightness of the house. If the air tightness of the house is high, a low air flow rate is sufficient to generate the desired indoor pressure level. If the tightness is poor, a larger air flow is needed to obtain the same pressure. In any case, this method increases the energy consumption through increased air exchange leading to heat losses.

Improving cellar ventilation

Improving cellar ventilation is a commonly used remediation method. The ventilation may be improved by cleaning and opening the vents or adding new ones. The ventilation can also be forced with a fan. It is also important to take care of the air tightness of the floor between the cellar and living area. Same applies for doors leading to the cellar.

The efficiency of the method is about 50%. Variation in the results from different countries can be seen in Table 32. In particular, Switzerland reported quite a high efficiency, as did Italy.

Table 32. Typical reduction factors reported by different countries for the remediation method "Improving cellar ventilation".

Country	Reduction factor (%), Typ. range
Austria	50
Czech Republic	25–50
Finland	20–55
France	47
Italy	60–90
Norway	10–50
Switzerland	75

The impact of cellar ventilation on energy consumption depends on the thermal insulation and air tightness between the cellar and living spaces, and on the type of ventilation and heating systems in the cellar. In general, the increasing air flow increases energy consumption.

Improving ventilation in the crawl space

Improving ventilation in the crawl space is a commonly used remediation method. The ventilation may be improved by cleaning and opening the vents or adding new ones. The ventilation can also be forced with a fan that can either blow air into or suck air from the crawl space. It is also important to ensure the air tightness of the floor between the crawl space and living area.

The efficiency of the method is typically 50%. Variation in the results from different countries can be seen in Table 33. In particular, Switzerland reported quite a high efficiency, as did Italy. In addition, the UK reported a radon reduction of 64% for mechanical ventilation of the under-floor space, and Portugal reported an efficiency of 60–80% for the building of a crawl space.

Table 33. Typical reduction factors reported by different countries for the remediation method "Improving crawl space ventilation".

Country	Reduction factor (%), Typ. range
Austria	50
Finland	40–65
France	47*
Italy	60–90
Norway	10–80
Switzerland	75
UK	47

* Same data as for cellar ventilation.

The impact of crawl space ventilation on energy consumption depends on the type of ventilation and on the thermal insulation between the crawl space and living spaces. Cooling of the floor is possible if the insulation is defective. If a fan is used, typical electrical powers are 50–70 W (BRE 2003) or lower.

Reducing under-pressure in the house

The air pressure in the living spaces is usually lower than that outdoors or in the sub-slab soil. This under-pressure is caused by the stack effect (i.e., by the indoor–outdoor temperature difference), by the wind effect and by possible mechanical ventilation of the house (if used). Under-pressure is usually largest for dwellings with mechanical exhaust ventilation (typically 4–10 Pa). For dwellings with natural ventilation and with mechanical supply and exhaust ventilation, it is 1–2 Pa and 2–5 Pa, respectively (Arvela and Reisbacka 2008b, 2009). Due to the under-pressure, radon-laden air is drawn from the sub-slab soil through cracks and holes in the base floor.

By reducing the under-pressure, the entry of radon-laden air can be restricted. With mechanical exhaust ventilation, this can be done by opening or installing more fresh air vents. With mechanical supply and exhaust ventilation, the under-pressure is adjusted by controlling the air flows in the ventilation system.

The efficiency of this method is typically limited to about 50–70%. Table 34 enumerates the values reported in the questionnaire by different countries. It should be noted that this method has rarely been used in Switzerland. The impact on energy consumption is similar to that of improving ventilation in living spaces.

Table 34. Typical range of radon reduction factor for the method "Reducing under-pressure in the house".

Country	Reduction factor (%), Typ. range
Austria	50
Norway	10–50
Switzerland	25
United Kingdom	60

4.3 Sealing entry routes

Typical entry routes include cracks, gaps, holes and pipe penetrations in the floor slab and in the floor edge. The gap in the joint between the floor slab and foundation wall due to drying shrinkage of the concrete slab is the most significant entry route. Porous foundation walls and basement walls made of lightweight concrete also offer a significant entry route. Sealing entry routes aims at reducing leakage flows of radon-bearing soil air into living spaces. Sealing may be very demanding, since the results are in many cases only satisfactory when the entry routes have been almost completely sealed. Floor joints with foundation and basement walls made of porous lightweight concrete are difficult to seal with normal methods.

Sealing entry routes is a commonly used remediation method and it is often used in combination with other methods. Typical reduction factors are in the range of 10–60%. Table 35 presents the values reported in the questionnaire by different countries.

Table 35. Typical range of radon reduction factors for the method "Sealing entry routes".

Country	Reduction factor (%), Typ. range
Austria	10
Czech Republic	10–40
Finland	10–55
France	55
Norway	10–60
Switzerland	25
United Kingdom	41

The impact of sealing entry routes on energy consumption is positive and dependent on the ventilation system used, since the method aims at reducing air leakage from the cold ground, which lowers the need for heating and hence decreases energy consumption. The impact could be significant for low and passive energy houses, for which the air tightness of the house envelope is considered important.

4.4 Radon well

Radon wells have been used in Finland, Italy, Norway, Sweden and Switzerland.

A radon well is constructed outside of the house, and the well sucks air from soil from a depth of 4–5 m. Figure 4 illustrates the principle of a radon well and Figure 5 its structure. This soil ventilation efficiently reduces the radon concentration of soil air below the house foundation and also in a large area surrounding the house. A single radon well can reduce the radon concentration in many dwellings at a distance of up to 20-30 m. A radon well is only effective in soils where air permeability is high enough, e.g. on gravel and in esker areas.

The efficiency is typically 80–90% (see Table 36). No significant impact on energy consumption of the house has been observed besides the electrical power required by the fan, which is typically 150–300 W.

Table 36. Typical range of radon reduction factors for the radon well.

Country	Reduction factor (%), Typ. range
Finland	80–90
Switzerland	90

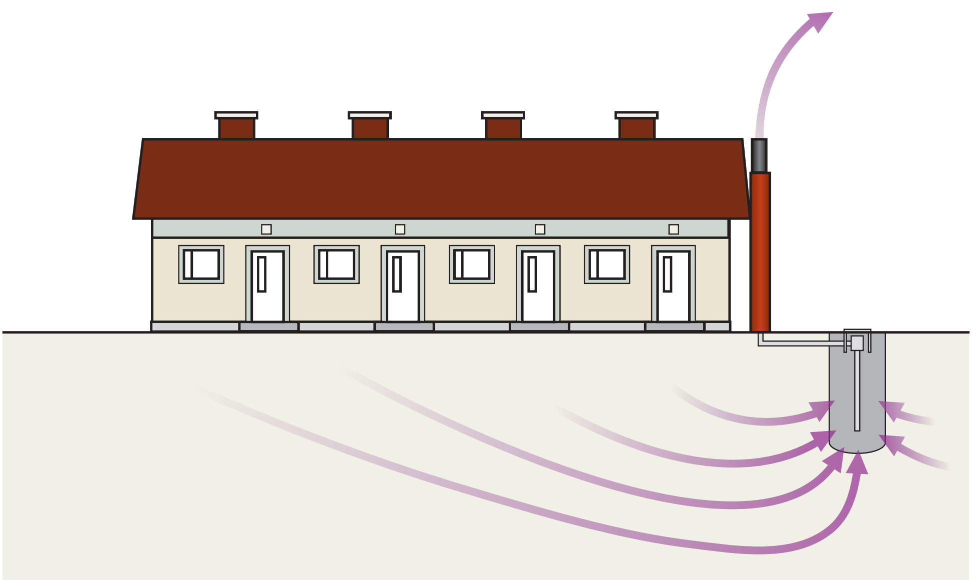

Figure 4. Principle of the radon well. It draws in air at a depth of 4–5 m and reduces the radon concentration of the soil air within large areas where the permeability is high enough (Arvela and Reisbacka 2008b, STUK-A229).

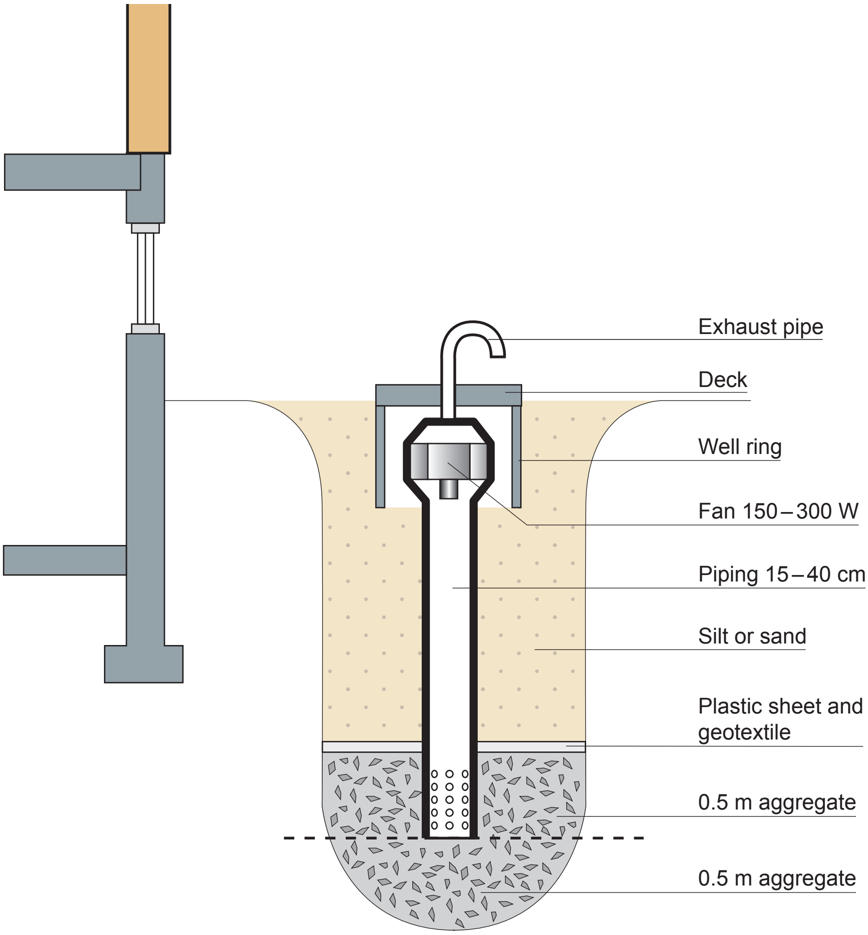

Figure 5. Detailed structure of a radon well. The total height of the well is about 5 m. The typical fan power is 150–370 W (Arvela and Reisbacka 2008b, STUK-A229).

4.5 Other methods

Soil ventilation through existing drainage piping

This method has similar features to sub-slab depressurisation. However, air is drawn from the ground through existing perforated drainage piping that is located outside the footings of the house instead of a sump or radon piping inside the perimeter of the house. Under appropriate conditions, a negative pressure field and soil ventilation are achieved over a large area, also covering the area beneath the house. The best results are probably obtained when the drainage piping is located below the level of the footing.

Soil air is sucked with a fan that can be connected to the drainage piping using one of the inspection wells or using a separate vertical pipe. The exit of the drainage system should be air tight enough such that adequate under-pressure can be created in the pipe with reasonable air flows. Even a special sealed valve can be installed at the exit of the drainage system (Swiss radon handbook 2000). The valve is opened by a sufficient quantity of water cancelling the force due to the under-pressure. The exit of the drainage system could also be equipped with a trap or water seal (CSTB 2008).

This method has been used at least in Switzerland. Recently it has also been assessed in Finland with a special focus on how applicable it is for the Finnish climate and building solutions.

The reported efficiencies are on average lower than those for SSD. Switzerland reported an efficiency of 50%, but it is effective only in 10% of cases (World Radon Solutions Database, 2003). In Finnish case studies, efficiencies of 50–90% have been measured. The potential impact on energy consumption can vary and depends on the potential cooling effects of the air flow in addition to the electrical power required by the fan.

New floors with a radon-proof membrane

This method has been used in the Czech Republic, where the structure of the new floor typically comprises a drainage layer of coarse gravel, radon piping in the drainage layer along the walls, geotextiles, a concrete slab, radon-proof membrane and thermal insulation.

The efficiency of this method is typically 35–45%. The method has a minimal impact on energy consumption in general. However, if the insulation of the floor is initially poor, the energy economics can be improved by adding proper thermal insulation.

A radon gas barrier has also been used in Portugal with radon reduction factors typically being 40–70%.

Active floor air gap ventilation

This remediation method can be constructed by removing the existing floor finish and by covering the concrete slab with plastic foil with dimples, which forms an air gap and serves as radon-proof barrier. The air gap is usually connected by a vertical exhaust pipe to a roof fan or rotating cowl that draws air from the gap. The height of the gap is usually 10–20 mm. Since the vertical exhaust pipe runs through the heated part of the house, it can be also used as a passive system creating a slight under-pressure in the gap without a fan.

This method has been used in the Czech Republic. The efficiency is reported to be typically 70–85%. The potential impact on energy consumption depends on the thermal insulation of the floor in addition to the electrical power consumed by the fan.

In Italy, a new floor upon the existing one with an air gap between has also been used.

Water treatment

Some private wells are drilled into the bedrock. The radon concentration of the water obtained from such drilled wells can be high. In such cases, the radon concentration in the house is usually increased, since radon is easily transferred to the indoor air from the water used in the kitchen, toilets and washrooms.

In Finland, some households have had high indoor radon concentration partly due to the high radon levels of the drilled well water. There are effective techniques to remove the radon from the water, such as water aeration and granular activated carbon filters. Several aeration techniques for removing radon have been introduced, including packed tower, diffused bubble, spray, and tray aeration. Instead of introducing radon-removing installations, house owners have in many cases abandoned the use of drilled wells and joined the municipal water network. By ending the use of the drilled well, the radon concentration has typically been reduced by 25–55%. In these households, radon concentration in household water was typically 1 000 – 10 000 Bq/l. The reference level for private wells is 1 000 Bq/l.

This method has a minimal impact on the energy consumption of the house. There is a slight increase due to the electrical power required by radon-removing devices.

Soil ventilation by exhaust air from the house

This method has been used in Norway and in Sweden. In Sweden, the method is called “Luftkuddemetoden” (in English, air cushion method).

The arrangement of this method is similar to that of SSD. However, it does not draw air from the ground beneath the slab but instead it blows air under the slab to reduce the amount of radon entering the building. In other words, the sub-slab soil is pressurized with air from inside the house. The method is based on the dilution of the radon concentration in sub-slab soil air. The system can be implemented with a 100 W fan at a single point in the middle of the slab exhausting air from the house to the sub-slab soil. The fan is equipped with a dust filter to prevent dust in the indoor air collecting in the sump. There could be a risk of condensation, since warm and humid air from the living space is pushed into the cold sub-slab soil. This risk should be considered in the design.

The efficiency of the method is 50–95% according to Norway’s questionnaire response. The impact of the method on energy consumption is similar to that for improving house ventilation. On the other hand, the temperature of the floor slab and sub-slab soil increases.

4.6 Typical combinations

In this section, different combinations of remediation methods are discussed based on the answers to the questionnaire. In general, the most efficient methods, such as SSD and radon wells, are recommended when the radon concentration is considerably above the reference level. Other methods based on sealing and ventilation measures can be used as complementary techniques. For example, sealing entry routes is normally not an adequate method alone.

Table 37 summarizes the typical combinations reported in the questionnaire. When combining a highly effective method with a less effective method, the reduction factor is dominated by the more efficient one, such as in the combination of sealing and SSD. Combining the sealing of entry routes with building ventilation has also resulted in high efficiencies, on average above 50%. Below, some of the combinations are further discussed.

Table 37. Efficiencies of typical combinations of methods.

Combination of methods	Reduction factor (%), Typ. range
Sealing + SSD (AUT)	80
New floors with radon-proof membrane + sub-slab depressurization (CZE)	85–95
New floors with radon-proof membrane + floor air gap depressurization (CZE)	80–90
Sealing + building ventilation (FRA)	72
Sealing + basement ventilation (FRA)	68
Building and basement ventilation (FRA)	67
Sealing entry routes + improving natural ventilation (NOR)	20–80
Several methods used (FIN)	35–75
Sealing + new mechanical supply and exhaust ventilation + house pressurization + reducing under-pressure (AUT)	80

New floors with a radon-proof membrane and sub-slab depressurization

This solution is designed to lower the air pressure under the building and at the same time to increase the air tightness of the floors. The structure of the new floor typically consists of a drainage layer of coarse gravel, radon piping in the drainage layer along the walls, geotextile, a concrete slab, radon-proof barrier and thermal insulation.

The radon piping is usually connected by a vertical exhaust pipe to a roof fan or rotating cowl that draws air from the gap. Since the vertical exhaust pipe runs through the heated part of the house, it can be also used as a passive system, creating a slight under-pressure in the gap without a fan.

The method has been used in the Czech Republic. The efficiency is reported to be typically 85–95%. The method has a minimal impact on energy consumption in general. However, if the insulation of the floor is initially poor, the energy economics can be improved by adding proper insulation with the new floor. The energy consumption is increased at least due to the electrical power required by the fan.

New floors with a radon-proof membrane and floor air-gap depressurization

This method combines the two methods described above on p. 63. The method has been used in the Czech Republic. The efficiency is reported to be typically 80–90%. The potential impact on energy consumption depends on the thermal insulation of the floor, in addition to the electrical power required by the fan. On the other hand, if the insulation of the floor is initially poor, the energy economics can be improved by adding proper insulation with the new floor.

4.7 Summary of remediation methods

The most common remediation methods used in European countries are summarized in Table 38. The radon reduction factors and potential impact on energy consumption are based on the questionnaire responses. The reduction factors and potential impact on energy consumption may vary according to the region and country due to differences in geology, climate and construction methods. The questionnaire responses of each country are discussed in previous sections and are also tabulated in Appendix 1.

Sub-slab depressurization is the most efficient remediation method, with typical reduction factors of 60–95%. The potential impact on energy consumption is negligible in most cases. In the case of excessive air flows sucked from the sub-slab soil, the floor could be cooled in cold climates if not properly thermally insulated. In addition, a fan requires electricity: for example, a fan of 70 W running for 24 h/day for 6 months consumes 300 kWh of electricity.

Improving ventilation in living spaces reduces the radon concentration by 10–60% on average, and reducing the under-pressure by 20–70%. In most case, the energy consumption is increased due to increased air exchange leading to higher heating costs. However, the installation of a new mechanical supply and exhaust ventilation system with heat recovery typically lowers energy consumption. Sufficient air exchange is a basic requirement not only for radon reduction but also for healthy indoor air.

House pressurization is commonly used in the UK only to reduce radon levels. Typical reduction factors are 40–80%. Depending on the air tightness of the house envelope it requires large air flows blown into the house to be effective, and hence the energy consumption is increased. In some countries (e.g., in Finland and Norway), the pressurization of the house is not even permitted in the building code due to the risk of condensation of moisture in the house envelope.

Improving ventilation in the cellar or crawl space reduces the indoor radon concentration by less than 60% on average. The impact on energy consumption depends on the thermal insulation and air tightness of the floor between the cellar/crawl space and living spaces. If fan-assisted ventilation is used, the electricity consumption of the fan should also be considered.

Sealing entry routes is not a very efficient remediation method: it only reduces the radon concentration by an average of 10–60%. However, it may have a positive impact on energy consumption, since the sealing of entry routes reduces the flow of cold air from the ground, which lowers the need for heating and hence decreases energy consumption, especially in low and passive energy houses.

Table 38. Radon reduction factors and potential impact on energy consumption for the most common remediation methods used in European countries.

Remediation method	Reduction factor (%), Typ. range	Potential impact on energy consumption
Sub-slab depressurization	70–95	Negligible impact in most cases. In the case of excessive air flows, floor could be cooled in cold climates if not properly insulated. Fan requires electricity, e.g., 300 kWh (70 W for 24 h/day for 6 months).
Improving natural ventilation in living spaces	10–50	Increases energy consumption due to increased air exchange.
Improving mechanical ventilation in living spaces	10–60	Increases energy consumption due to increased air exchange.
Replacing the existing natural room air ventilation with mechanical exhaust ventilation	10–40	Increases energy consumption due to increased air exchange.
Installation of a new mechanical supply and exhaust ventilation system with heat recovery	30–60	Decreases typically energy consumption.
House pressurization, (higher pressure indoors than in the soil under the floor)	40–80	Increases energy consumption due to increased air exchange.
Improving cellar ventilation	20–60	Depends on the thermal insulation and air tightness of the floor between the cellar/crawl space and living spaces.
Improving crawl space ventilation	40–60	Depends on the thermal insulation and air tightness of the floor between the cellar/crawl space and living spaces.
Reducing under-pressure in the house	20–70	
Sealing entry routes	10–60	Positive impact, sealing entry routes decreases air flow from the ground and hence decreases energy consumption, especially in low and passive energy houses.

5 Prevention methods

In this section, radon prevention methods in new buildings are discussed. Preventive measures are taken during the construction of a building and significantly reduce the indoor radon concentration. Furthermore, appropriate preventive measures provide a potential means to lower the radon concentration at low cost and with little disruption if the radon concentration is found to be excessive when the building is in use.

As discussed in the WHO Handbook on Indoor Radon (WHO 2009), most prevention methods include steps to limit soil gas infiltration due to air pressure differences between the soil and the indoor space. Radon prevention methods should consider the specific mix of construction practices, radon sources, and transport mechanisms specific in the region or country, in order to be cost-effective. Under certain conditions, a combination of strategies may be necessary.

In some countries, the scope of preventive measures applied in new construction is decided on the basis of radon risk maps that can be assessed using a number of different approaches. The most common approach involves the mapping of indoor radon concentrations in existing houses and is sometimes complemented by geological information. Another approach used in some countries, such as the Czech Republic, involves testing individual building sites before construction using soil gas and soil permeability measurements to establish a radon index. The index is then used to define the degree of radon protection needed for the building on that site. However, in countries including Finland, Ireland, Norway, Sweden, Switzerland, the UK, and USA, the most cost-effective approach appears to be the use of radon prevention in all new buildings. Sometimes, this approach is restricted to radon-prone areas. (WHO 2009)

The choice of foundation types strongly affects the prevention work needed in the building process. In most radon critical areas, foundation techniques that commonly result in low radon concentrations are preferable. For example, a crawl space (or suspended floor) and monolithic slab require less prevention work compared with slab-on-ground and basement houses. Stepped foundations, however, complicate the implementation of radon preventive measures.

Radon risk maps may also have negative consequences: they may lead to a false belief in low indoor radon concentrations. Low-radon areas may also include local areas (or hot spots) with more radon-prone soil types. The widespread use of radon prevention may prevent unexpectedly high radon concentrations in new construction.

From the radiation protection point of view, and based on the ALARA principle (as low as reasonably achievable), radon resistant construction should be used in all buildings or over wide areas rather than only in restricted areas.

5.1 Sub-slab depressurization

Preparatory, passive and active sub-slab depressurization (SSD) systems are common prevention methods used in most of the RADPAR countries.

In a preparatory SSD system, a radon sump or a network of piping is installed beneath the floor slab during the construction of the house. This system can later be taken into use and activated if the radon concentration exceeds the reference level. The exhaust duct of the system can be sealed inside the house or it can be led through the house onto the roof to open air. In the latter case, the system is called here as passive SSD, since the stack and effects of the wind induce flow in the exhaust duct, resulting in sub-floor ventilation and depressurization. If the indoor radon level still exceeds the reference level, the system can be activated by installing a fan in the exhaust duct (and is then referred to as active SSD).

According to the questionnaire responses (Table 39), passive SSD typically lowers the radon concentration by 30–50% and active SSD typically by 70–95%. Portugal reported lower efficiencies for active SSD than other countries. In Finland, the efficiency of SSD systems may be decreased in some cases if highly permeable crushed stone is used underneath the floor slab, foundations and footings. In this case, the under-pressure is not well developed, since the system draws too much air directly from outside the foundation.

The impact of passive and active SSD on energy consumption is the same as in the remediation discussed in Section 4.1 on page 55.

Table 39. Efficiencies of passive and active SSD reported in the questionnaire responses.

Country	Reduction factor (%), Typ. range	
	Passive	Active
Finland	30–40	70–90
Norway	0–20	70–95
Portugal	20–50	40–70
Switzerland	50	95

5.2 Radon-proof barrier

Membrane above or below the floor slab

Membranes above or below the floor slab are commonly used in European countries, according to the questionnaire responses (see Table 40). Finland is the only country where membranes are not used over the whole base floor area, but instead a strip of reinforced bitumen felt is placed in the floor–wall joint.

Table 40. Usage of membranes in the base floor.

Country	Membrane below floor slab	Membrane above floor slab
Austria	Yes	Yes
Belgium	Yes	Yes
Czech Republic	No	Yes
Finland	No*	No
France		
Germany	Yes	Yes
Greece	Yes	Yes
Ireland	Yes	Yes
Norway	No	Yes
Portugal		Yes
Spain		
Switzerland	Yes	Yes
United Kingdom	Yes	Yes

* replaced by a strip of bitumen felt in the floor-wall joint

In many cases, a damp-proof membrane provides an adequate radon-proof barrier, along with the general function of excluding moisture. In all cases, the air tightness of joints and pipe penetrations is important, as well as an airtight connection to walls. Therefore, high standards of design and workmanship are needed to obtain a continuous barrier against radon. Damage during construction should also be avoided. Even a tiny air leakage could lead to high indoor radon concentrations.

Table 41 presents the efficiencies of the method "Membrane above the floor slab" reported in the questionnaire. The reduction factor is typically around 50%. The impact on energy consumption is negligible in conventional construction. In low energy and passive houses, it may have a positive impact, since an attempt is made to eliminate all air leakages to minimize energy consumption. Therefore, radon prevention and low energy construction have the same goal of minimizing air leakages from the soil beneath the house.

Table 41. Efficiency of the method "Radon-proof barrier, membrane above floor slab".

Country	Reduction factor (%), Typ. range
Czech Republic	30–70
Norway	0–90
Portugal	30–60
Switzerland	50
United Kingdom	50

Sealing

Sealing the joint between the floor slab and foundation wall using membranes is naturally included in the previous method, where a membrane is placed over the entire base floor. In Finland, where such membranes are not used, only the joint between the floor slab and foundation wall is sealed with a strip of membrane (usually reinforced bitumen felt). Sealing of pipe penetrations in structures with soil contact is recommended in many countries.

Table 42 presents the efficiencies of sealing methods according to the questionnaire responses. In most cases, sealing measures have been taken simultaneously with a membrane and SSD installations. Therefore, efficiency data for sealing measures used alone are lacking.

Table 42. Efficiencies of sealing methods.

	Reduction factor (%), Typ. range	
Prevention method	**NO**	**CH**
Sealing the joint between floor slab and foundation wall with membranes	0–90	30
Sealing pipe penetrations in structures with soil contact	0–90	50

5.3 Other prevention methods

Use of waterproof concrete instead of normal concrete

The method "Use of waterproof concrete instead of normal concrete" is used in Austria, Germany and Greece. No efficiency data for the method were reported in the questionnaire responses.

Double radon-proof membrane

A double radon-proof membrane placed above the floor slab and combined with depressurization of the space between the membranes was reported by Germany. No efficiency data were reported in the questionnaire response.

Preparatory soil ventilation using exhaust air from the house

A preparatory arrangement for sub-slab or crawl space ventilation using exhaust air from the house was reported by Norway. A fan is only installed if the radon level is found to be higher than the reference level. The efficiency of the method and impact on energy consumption are discussed on p. 64.

Passive ventilation under suspended concrete floor

Passive ventilation under a suspended concrete floor has been used in the UK. An efficiency of 50% was reported in the UK's questionnaire response.

Portugal reported that the efficiency of the method "Building a crawl space" is 70–90%. However, this may be an unrepresentative result, since the efficiency is only based on a few houses where preventive measures have been used in a local area.

5.4 Typical combinations

Combinations are typically used in high radon areas. For example, a radon-proof membrane combined with active or passive sub-slab depressurization (SSD) is recommended in many countries. Similarly, active or passive floor air gap ventilation can be used with a radon-proof membrane, as reported by the Czech Republic. In Finland, passive SSD and sealing the joint between the floor slab and foundation wall with reinforced bitumen felt is used. Table 43 provides the efficiencies of these combinations. In addition, sealing of pipe penetrations should always be done, since this is an easy, rapid and inexpensive method to prevent radon from entering the house.

Table 43. Efficiencies of combinations of prevention methods used in the Czech Republic and in Finland.

Combination of methods	Reduction factor (%), Typ. range
Radon-proof membrane above floor slab + active or passive SSD (CZE)	40–80
Passive SSD + sealing the joint between floor slab and foundation wall with bitumen felt (FIN)	40–60

5.5 Summary of prevention methods

The most common prevention methods used in European countries are summarized in Table 44. Radon reduction factors and potential impact on energy consumption are based on the questionnaire responses. The reduction factors and potential impact on energy consumption may vary according to the region and country due to differences in geology, climate and construction methods. The questionnaire responses of each country are discussed in previous sections and they are also tabulated in Appendix 1.

In many countries, provisional sub-slab depressurization (SSD) is required, meaning that a radon sump or radon piping (i.e., a network of flexible perforated pipes) is placed in a sub-floor layer of coarse gravel during the construction of the house. The exhaust duct of the sump or piping can be either capped or open above the roof. In the latter case, the system (passive SSD) reduces the radon concentration on average by 20–50% compared to the situation where the sump or piping is capped or there is no provision for SSD. An active (i.e., fan-assisted) system is the most efficient prevention method, with a typical reduction factor of 70–95%.

The potential impact of passive and active SSD on energy consumption is negligible in most cases. In the case of excessive air flows sucked from the sub-slab soil, the floor could be cooled in cold climates if the base floor is not properly thermally insulated. In addition, the fan requires electricity: for example, a fan of 70 W running for 24 h/day for 6 months consumes 300 kWh of electricity.

Radon-proof barrier with a membrane reduces the radon concentration on average by 50%. Concerning the effect of sealing-based methods, research data are lacking and hence a wide range for the typical reduction factor has been adopted. The potential impact on energy consumption is positive, since the use of membranes and sealing of entry routes reduces the air flow from the ground, which lowers the need for heating and hence decreases energy consumption, especially in low and passive energy houses.

Table 44. Typical radon reduction factors and potential impact on energy consumption for typical prevention methods used in European countries.

Method	Reduction factor (%), Typ. range	Potential impact on energy consumption
Passive SSD	20–50	Negligible
Active SSD	70–95	Negligible impact in most cases. In the case of excessive air flows, floor can be cooled in cold climates if not properly insulated. Fan requires electricity, e.g., 300 kWh (70W for 24 h/day for 6 months).
Radon-proof barrier, membrane below floor slab	30–70	Positive impact, sealing entry routes decreases air flow from the ground and hence decreases energy consumption, especially in low and passive energy houses
Radon-proof barrier, membrane above floor slab	30–70	
Sealing the joint between floor slab and foundation wall with membranes	10–90	
Sealing pipe penetrations in structures with soil contact	10–90	

6 Conclusions

In this report, current techniques/technologies used to achieve the reduction of indoor radon concentrations in existing and new houses have been analysed and assessed with regard to reduction efficiency and the potential impact on energy consumption (qualitative). A questionnaire dealing with these issues was sent to all RADPAR partners in 14 different countries. Variable amounts of information were obtained. Based on the questionnaire responses, the status of radon remediation and prevention in each country was assessed, in addition to the reduction efficiency and potential impact on energy consumption of the current remediation and prevention techniques.

The number of houses with an elevated indoor radon concentration typically ranges from tens of thousands to a million. The percentage of houses already remediated varies from zero to 15%. Preventive measures in new construction have been taken in a small number of houses up to over half a million houses. Research data on the current situation, the number of houses with preventive measures and the efficiency of these measures are currently still quite inadequate. Assessment of the techniques and also surveys aiming at exploring the impact of remedial and preventive measures are greatly needed in order to promote the work at the national level.

The most efficient remediation method is the active sub-slab depressurization (SSD) and radon well, for which the reduction in radon concentrations is typically 70–95%. Other methods, such as sealing entry routes and improving ventilation in living spaces, in the cellar or in the crawl space, are less effective: the reduction of radon concentrations is typically 10–60%. The efficiencies of prevention techniques are analogous to those of remediation techniques. Active SSD is the most efficient prevention technique. The efficiency of passive SSD and passive radon piping is lower, typically 20–50%. However, the widespread use of such systems can be recommended. Radon-proof barrier in the base floor reduces the radon concentration on average by 50%.

The impact of remedial techniques and preventive techniques on energy consumption is significant for active SSD, mainly due to the power consumption of the electrical fan used, and potentially also to a lesser degree due to cooling of the base floor. The impact on energy consumption of passive SSD and passive radon piping is negligible. The sealing of entry routes in both remediation and prevention in new construction has a positive impact through reduction of the leakage of cold air from the ground in low energy and passive houses. Replacing existing natural or mechanical exhaust ventilation with a new mechanical supply and exhaust ventilation system with heat recovery can reduce energy consumption. On the other hand, other methods increasing ventilation in living spaces reduce the radon concentration but simultaneously increase energy consumption due to increased air exchange.

The sealing of house foundations in contact with soil and control of air flows in standard, low energy and passive construction have synergistic goals. The reduction of soil-air flows into the house reduces indoor radon concentrations and simultaneously also energy consumption.

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APPENDIX 1: QUESTIONNAIRE RESPONSES

Table A 1. Filled in by, Organisation.

Austria	Wolfgang Ringer, Austrian Agency for Health and Food Safety
Belgium	Jean Klerkx + André Poffijn, IBES + Federal Agency for Nuclear Control
Czech Republic	M. Jiránek, K. Rovenská, I. Fojtíková, CTU Prague + NRPI (SURO) Prague
Finland	Olli Holmgren + Hannu Arvela, Radiation and Nuclear Safety Authority – STUK
France	Bernard Collignan, CSTB
Germany	Bernd Hoffmann, Federal Office for Radiation Protection
Greece	John Bartzis, Environmental Technology Laboratory, Dep. of Mechanical Engineering, University of Western Macedonia (UOWM)
Ireland	Radon Advice Section, Radiological Protection Institute of Ireland
Italy	Francesco Bochicchio, Italian National Institute of Health
Norway	Will Standring, Norwegian Radiation Protection Authority
Portugal	Eduardo de Oliveira Fernandes, University of Porto
Spain	Luis Santiago Quindos Poncela, University of Cantabria
Switzerland	Martha Gruson, Federal office of public health (FOPH) + Claudio Valsangiacomo, Radon competence centre SUPSI
United Kingdom	Jon Miles, Health Protection Agency

Table A 2. Action and target levels for radon remediation and prevention (questions A1.1. & B1.1.).

Country	Action level (Bq/m³)	Target level (Bq/m³)	Mandatory/ recommendation
Austria	400	200	rec
Belgium	400	200	rec
Czech Republic	400	200	rec
Finland	400	200	man
France	400	–	–
Germany	100	100	rec
Greece	400	200	rec
Ireland	200	200	rec
Italy	–	–	–
Norway, 100	100	100	rec
Norway, 200	200	100	rec
Portugal	400	400	rec
Spain	–	–	–
Switzerland, 1 000	1 000	400	man
Switzerland, 400	400	400	rec
United Kingdom	200	200	rec

Table A 3. Number of dwellings in low-rise residential and in apartment buildings (question A1.2.).

Country	Total number		Exceeding		Remediated	
	Low-rise	Apartment	Low-rise	Apartment	Low-rise	Apartment
Austria	1 900 000	1 800 000	80 000	9 000	25	0
Belgium in radon prone zone	3 612 000 68 000	1 431 000	20 000 10 000		1 000	
Czech Republic	1 640 000	2 200 000	33 000	4 000	2 350	35
Finland	1 350 000	1 100 000	51 000	8 000	3 000	250
France	18 625 000	14 131 000	968 500			
Germany	18 300 000	21 600 000	1 930 000		1 000	
Greece	2 780 050	2 847 499				
Ireland	1 740 600	193 400	91 000			
Italy	22 000 000				100	
Norway, 100 Norway, 200	1 779 689 1 779 689	494 673 494 673	387 600 147 663	39 375 14 840		
Portugal			2.6%	2.6%		
Spain						
Switzerland, 1 000 Switzerland, 400	4 000 000 4 000 000		5 000 – 10 000 50 000 – 100 000		500	
United Kingdom	23 000 000		100 000		15 000	

Table A 4. Use of remediation methods (question A2).

Method	AT	BE	CZ	FI	FR	DE	GR	IE	IT	NO	PT	ES	CH	UK
Sub-slab depressurization	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	D		YES	YES
Improving natural ventilation in living spaces	No	No	YES	YES	YES	D	YES	YES	No	YES	YES		YES	YES
Improving mechanical ventilation in living spaces	No	YES	No	YES	YES	D	YES	YES	YES	YES	YES		YES	YES
Replacing the existing natural room air ventilation with mechanical exhaust ventilation	No	?	No	YES	D	YES	YES	D	D	YES	YES		YES	No
Installation of a new mechanical supply and exhaust ventilation system with heat recovery	YES	?	YES	YES	D	D	No	YES	YES	YES	D		YES	No
House pressurization (higher pressure indoors than in the soil under the floor)	YES	No	YES	No	D	YES	No	YES	YES	No	D		YES	YES
Improving cellar ventilation	YES	YES	YES	YES	YES	D	YES	D	YES	YES	D		YES	YES
Reducing under-pressure in the house	YES	No	No	YES		D	No	YES	YES	YES	D		YES	YES
Sealing entry routes	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES		YES	YES
Improving crawl space ventilation	YES	YES	YES	YES	YES	D	No	D	YES	YES	D		YES	YES
Radon well (soil ventilation, outside the house)	No	No	No	YES	No	D	No	D	YES	No	D		YES	No
Soil ventilation through existing drainage piping outside the footings	No	No	No	YES	D	D	No	D	No	No	D		YES	No

D = Do not know

Table A 5. Remediation methods, reduction factor (%), typical range (question A2).

Method	AT	BE	CZ	FI	FR	DE	GR	IE	IT	NO	PT	ES	CH	UK
Sub-slab depressurization	80	90	85–95	65–95	89				60–95	50–95	D		90	89
Improving natural ventilation in living spaces			<30	15–55	49					10–50	D		D	33
Improving mechanical ventilation in living spaces		Low		5–55	61				20–95	10–20	D		D	D
Replacing the existing natural room air ventilation with mechanical exhaust ventilation				15–45						10–20	D		D	
Installation of a new mechanical supply and exhaust ventilation system with heat recovery	60		30–60	30–65						10–80	D		D	
House pressurization (higher pressure indoors than in the soil under the floor)	80		D						60–95		D		D	D
Improving cellar ventilation	50	Limited	25–50	20–55	47				60–90	10–50	D		75	D
Reducing under-pressure in the house	50									10–50	D		25	60
Sealing entry routes	10	Sometimes effective	10–40	10–55	55					10–60	D		25	41
Improving crawl space ventilation	50	?	D	40–65	47				60–90	10–80	D		75	47
Radon well (soil ventilation, outside the house)				80–90							D		90	
Soil ventilation through existing drainage piping outside the footings											D		50	

D = Do not know

Table A 6. Remediation methods and potential impact on energy consumption (question A2).

Method	AT	CZ	FI	IT	NO	CH
Sub-slab depressurization	Negligible	Minimal	No significant effect if air flows are below the rated values (0.2–0.5 m3/h per m2 of slab)	Low	Moderate impact. Floor can in some cases be cooled if not insulated.	ca 300 kWh for the whole heating season (Fan of 70 W, 24 h a day for 6 months)
Improving natural ventilation in living spaces		Proportional to ventilation rate	Increasing air flows always increase energy consumption		High impact	Do not know (rarely used)
Improving mechanical ventilation in living spaces			Increasing air flows always increase energy consumption	High	High impact	Do not know (rarely used)
Replacing the existing natural room air ventilation with mechanical exhaust ventilation			Increasing air flows always increase energy consumption.		High impact	Do not know (rarely used)
Installation of a new mechanical supply and exhaust ventilation system with heat recovery	Negligible	In winter when using the pre-heating unit unacceptable high, in summer minimal	Decrease in energy consumption		Moderate impact. Energy consumption normally increases if initial ventilation rate is low, which is a condition for the effectiveness of this method.	Do not know (rarely used)
House pressurization (higher pressure indoors than in the soil under the floor)	Negligible	In dependence on the house tightness			(Not recommended in Norwegian houses due to risk of moisture problems)	Do not know (rarely used) Very dangerous solution if ceiling permeable to radon!
Improving cellar ventilation			Increasing air flows always increase energy consumption	Medium	Moderate to high impact	Cheap and often effective ca 300 kWh for the whole heating season (Fan ...)
Reducing under-pressure in the house	Negligible		Variable, depends on ventilation strategy		Could be both positive or negative depending of method	Do not know (rarely used)
Sealing entry routes	No	No impact	No effect due to small air flows		Moderate impact - positive	Often used but modest results, no effect on energy consumption
Improving crawl space ventilation	Cooling of floor slab possible, but usually not a real problem	In dependence on the ceiling tightness	Increase in energy consumption, if thermal insulation is defective	Low	Moderate impact – depending on type of ventilation and insulation between crawl space and living spaces	Very effective when crawl space present
Radon well (soil ventilation, outside the house)			No significant effect observed			Often used ca 300 kWh for the whole heating season (Fan ...)
Soil ventilation through existing drainage piping outside the footings			No significant effect if air flows are below the rated values			Use sometimes if existing pipe has good coverage areas below building. ca 300 kWh for the whole heating season (Fan ...)

Table A 7. Reduction factors and potential impact on energy consumption for other remediation methods and combinations reported (question A2).

Other methods	**Country**	**Reduction factor (%), Typ. range**	**Potential impact on energy consumption**
New floors with radon-proof membrane	CZE	35–45	No impact
Active floor air gap ventilation	CZE	70–85	In dependence on the air gap tightness
Stop using water from drilled well	FIN	25–55	No effect on energy consumption
Reducing under-pressure in the house with insufflating mechanical ventilation	FRA	81	
Soil ventilation by exhaust air from house	NOR	50–95	Low impact
Mechanical ventilation of underfloor space	UK	64	
Radon gas barrier	POR	40–70	
Building of crawl space	POR	60–80	
Adding of a new floor upon the existing one with a cavity wall below	ITA		
Combinations	**Country**	**Reduction factor (%), Typ. range**	**Potential impact on energy consumption**
Sealing + SSD	AUT	80	Negligible
New floors with radon-proof membrane + sub-slab depressurization	CZE	85–95	Minimal
New floors with radon-proof membrane + floor air gap depressurization	CZE	80–90	Minimal
Sealing + building ventilation	FRA	72	
Sealing + basement ventilation	FRA	68	
Building and basement ventilation	FRA	67	
Sealing entry routes + improving natural ventilation	NOR	20–80	High impact
Several methods used	FIN	35–75	
Sealing + new mechanical supply and exhaust ventilation + house pressurization + reducing under-pressure	AUT	80	Negligible
Sealing entry routes + sub-slab depressurization	ITA		

Table A 8. References (question A3).

Country	A3 References, guides for mitigation , brochures, research reports, website links, other relevant documents
Austria	– ICS 13.280 Radon – Part 3: Remedial measures on buildings (in German) – Maringer FJ et al. Results and conclusions of the Austrian radon mitigation project 'SARAH'. The Science of The Total Environment 2001; 272 (1–3): 159–167. – Brochure "Radonbelastung in Oesterreich" (in German) – *www.strahlenschutz.gv.at* (in German)
Belgium	– Le Radon et votre habitation: méthodes de remédiation et de prévention, 30 p., AFCN – Le radon dans les habitations: mesures préventives et curatives – Note d'information technique 211, Centre Scientifique et Technique de la Construction, 1999. – *www.fanc.fgov.be* – *www.ibes.be/radon* – *www.ecoterra.be*
Czech Republic	– ČSN 73 0601 Protection of buildings against radon from the soil (Czech technical standard) – ČSN 73 0602 Protection of buildings against radon and gamma radiation from buildings materials (Czech technical standard) – Jiránek M, Neznal M, Neznal M. Mitigation of ineffective measures against radon. Radiation Protection Dosimetry 2008; 130 (1): 68–71. DOI:10.1093/rpd/ncn120 – Jiránek M, Rovenská K. Limited applicability of cost-effectiveness and cost-benefit analyses for the optimization of radon remedial measures. Journal of Hazardous Materials 2010; 182 (1–3): 439–446. DOI: 10.1016/j.jhazmat.2010.06.051
Finland	Guides 1. Arvela H, Reisbacka H. Asuntojen radonkorjaaminen (Indoor radon mitigation). STUK-A229. Helsinki: Radiation and Nuclear Safety Authority; 2008. 131 pp. (In Finnish, abstract in English, national mitigation guide). 2. Arvela H, Reisbacka H. Radonsanering av bostäder (Indoor radon mitigation). STUK-A237. Helsinki: Radiation and Nuclear Safety Authority; 2009. (In Swedish, abstract in English, national mitigation guide, Swedish translation of STUK-A229). 3. Radon remediation of low-rise residential houses. Sub-slab-depressurization. Ministry of Environment. Environmental guide 4. Helsinki: Oy Edita Ab; 1996. 44 pp. (In Finnish) Research reports 1. Arvela H, Reisbacka H, Keränen P. Radon prevention and mitigation in Finland: Guidance and practices. In: Proceedings of the American Association of Radon Scientists and Technologists AARST 2008 International Symposium. 2008 Sep 14–17; Las Vegas NV, USA. (Available at *www.aarst.org*). 2. Arvela H, Reisbacka H. New indoor radon mitigation guides in Finland. In: Nordic Society for Radiation Protection – NSFS. Proceedings of the NSFS XV conference in Ålesund Norway, 26– 30 of May 2008. StrålevernRapport 2008:13. Østerås: Norwegian Radiation Protection Authority; 2008. p. 121–124. 3. Reisbacka H. Radon mitigation in large buildings in Finland. In: Valentin J, Cederlund T, Drake P, Finne IE, Glansholm A, Jaworska A, Paile W, Rahola T (eds). Radiological Protection in Transition – Proceedings of the XIV Regular Meeting of the Nordic Society for Radiation Protection, NSFS – Rättvik, Sweden, 27–31 August 2005. SSI Report 2005:15. Stockholm: Swedish Radiation Protection Authority; 2005. p. 225–227. 4. Arvela H. Radon mitigation in blocks of flats. The Science of the Total Environment 2001; 272 (1–3): 137. 5. Arvela H., Castrén O. Asuntojen radonkorjauksen kustannukset Suomessa (Costs of radon remediation in Finland). STUK-A114. Helsinki: Radiation and Nuclear Safety Authority; 1994. (In Finnish) 6. Arvela H., Hoving P. Finnish experiences in indoor radon mitigation. In: Proceedings of the 6th International Conference on Indoor Air Quality and Climate. Vol 4. 1993 July 4–8; Helsinki, Finland. p. 563–568. 7. Hoving P, Arvela H. Effectiveness of ventilation improvements as a protective measure against radon. In: Proceedings of the 6th International Conference on Indoor Air Quality and Climate. Vol 4. 1993 July 4–8, Helsinki, Finland. p. 615–620. Website links 1. *www.radon.fi* 2. *www.stuk.fi*
France	– Le radon dans les bâtiments. Guide pour la remédiation dans les constructions existantes et la prévention dans les constructions neuves. Guide technique CSTB, juillet 2008. (In French) – Collignan B, Abdelouhab M, Allard F. Experimental study on passive sub-slab depressurisation system. In: AARST's 18th International Radon Symposium. 2008 Sep14–17; Las Vegas, USA. – Collignan B, O'Kelly P, Pilch E. Basement depressurisation using dwelling mechanical exhaust ventilation system. In: 4th European Conference on Protection against radon at home and at work. 2004 Jun 28 – Jul 2; Praha. – Collignan B, O'Kelly P. Dimensioning of soil depressurization system for radon remediation in existing buildings. In: Proceedings of ISIAQ 7th International Conference Healthy Buildings. Vol. 1. 2003 Dec 7–11; Singapore. p. 517–523. – Collignan B, Millet JR. Estimation of radon concentration in house using a simple ventilation model. In: Radon in the living environment. Athens workshop. 1999 Apr 19–23; Athens, Greece. *ese.cstb.fr/radon*

Table A 8. Continued.

Country	A3 References, guides for mitigation , brochures, research reports, website links, other relevant documents
Germany	Radon-Handbuch Deutschland *www.bfs.de/en/ion/radon*
Greece	– Greek Atomic Energy Commission – The radon at primary schools of Lesvos Island, Aegean University – General Secretariat of the National Statistical Service of Greece – Technical Chamber of Greece – COMMISSION RECOMMENDATION of 21 February 1990 on the protection of the public against indoor exposure to radon. 90/143/Euratom.
Ireland	– Radon in existing buildings – Corrective options. *www.environ.ie/en/Environment/EnvironmentalRadiation/PublicationsDocuments/FileDownLoad,1327,en.pdf* – Understanding radon remediation – A householders guide. *www.rpii.ie/CMSPages/GetFile.aspx?nodeguid=4ece68d5-a1e3-4e9f-96b1-a327c45e2c01&PublicationID=688* – Synnott H, Colgan PA, Hanley O, Fenton D. The effectiveness of radon remediation in Irish schools. Health Physics 2007; 92 (1): 50–57. – Action plan to identify and remedy Irish houses with radon concentrations above the national reference level. *www.rpii.ie/CMSPages/GetFile.aspx?nodeguid=0a690430-3f77-484f-8c75-29d31df2ed16&PublicationID=2236*
Italy	– Minach L, Giovani C, Garavaglia M. Linee guida relative ad alcune tipologie di azioni di risanamento per la riduzione del radon (Guidelines referring to some remediation methods for radon reduction in buildings). APAT –RTI CTN_AGF 4/2005. (In Italian only, available at *www.arpa.umbria.it/au/sinanet/Radiazioni%20Ionizzanti/IR_04/AGF-T-LGU-04-03.pdf*.) – Bertagnin M, Garavaglia M, Giovani C, Russo G, Villalta R. 2003 – Indicazioni e proposte per la protezione degli edifici dal radon – ARPA Friuli Venezia Giulia (32 pages). This is a comprehensive brochure by the Environmental Protection Agency of the Friuli-Venezia Giulia Region. (In Italian only, available at *www.arpa.fvg.it/fileadmin/Informazione/Pubblicazioni/pubbl_radiazioni/radon-IndicazioniProtezioneEdifici.zip*.) – Torri G, Feroce C, Giangrasso M, Notaro M. Remedial action in buildings with high radon concentrations – applications in a few Italian dwellings. Radiation Protection Dosimetry 1998; 78 (1): 45–48. – *www.provincia.bz.it/agenzia-ambiente/radiazioni/contromisure.asp* Link to the webpage (in Italian and German) of the "Provincia Autonoma di Bolzano" that describes the remediation methods used by the local Environmental Agency. This page contains links to other relevant documents and websites. – ARPAV. Sperimentazione delle azioni di rimedio sugli edifici con alta concentrazione di gas radon nel Veneto. 2007. This is a research report (in Italian) by the Environmental Protection Agency of the Veneto Region. It contains the description of radon mitigation methods and some experimental results of the efficiency of radon reduction for a group of houses with high radon concentration (available at *www.arpa.veneto.it/agenti_fisici/docs/radon/Rapportobonifiche2007.pdf*).
Norway	– Byggforsk: Tiltak mot radon I eksisterende bygninger. Byggforskserien, Byggforvaltning 701.706, Sending 1 – 2006. – Statens bygningstekniske etat: Radon, temaveiledning. Melding HO-3/2001, BE, NRPA, Norges byggforskningsinstitutt; 2001.
Portugal	– Radon levels in dwellings. WHO; 2007. *www.who.int/en/* – Survey on radon guidelines, programmes and activities. WHO; 2007. *www.who.int/en/* – Consumer's guide to radon reduction. US-EPA; 2006. *www.epa.gov/radon/pdfs/consguid.pdf* – A citizen's guide to radon. The guide to protecting yourself and your family from radon. US EPA; 2005. *www.epa.gov/radon/pdfs/citizensguide.pdf* – International radon project. Indoor air quality: a risk based approach to health criteria for radon indoors. WHO; 1996. (In particular Chapter 3: Policy Issues) *www.who.int/ionizing_radiation/env/radon/WHOEUROReport1996.pdf* – Report Nº 15: Radon in indoor air. ECA; 1995. *www.inive.org/medias/ECA/ECA_Report15.pdf* – Towards healthy air in dwellings in Europe. *www.efanet.org/activities/documents/THADEReport.pdf* – Building Research Establishment (BRE). *www.bre.co.uk/radon* – Oliveira Fernandes E, Jantunen M, Carrer P, Seppänen O, Harrison P, Kephalopoulos S. Publishable final report: Policies on indoor air quality: assessment and needs. ENVIE Project. European Commission 6th Framework Programme of Research. Brussels; 2008. – Dubois G. An overview of radon surveys in Europe. Luxembourg: Office for Official Publications of the European Communities; 2005. EUR 21892 EN. – Building radon out. A step by step guide on how to build radon-resistant homes. EPA/402-k-01-002; April 2001. – National approaches to controlling exposure to radon. Environment International 1996; 22 (Supplement 1): 1083–1092. – Indoor radon concentrations in Portugal – a national survey. Radiation Protection Dosimetry 1992; 45 (1/4): 465–467.
Spain	– NO GUIDES FOR REMEDIATION – *www.elradon.com* is a page with a lot of information about radon

Table A 8. Continued.

Country	A3 References, guides for mitigation , brochures, research reports, website links, other relevant documents

Switzerland	– Websites: www.ch-radon.ch (in French, German, Italian, English)
	– Website (chapter "documentation" in the menu on the right side):
	  – Swiss radon handbook (in French, German, Italian, English)
	  – Information booklets (in French, German and Italian)
	– Website (chapter "documentation" in the menu on the right side, click on "legal foundations"):
	  – Ordinance on radiation protection (in French, German, Italian, English)
	– World radon solutions database: www.worldradonsolutions.info/

United Kingdom	– Naismith SP, Miles JCH, Scivyer CR. The influence of house characteristics on the effectiveness of radon remedial measures. Health Physics 1998; 75: 410–416. – Radon sump systems: BRE guide to radon remedial measures in existing dwellings. BRE report BR227. Authors: Scivyer C, Cripps A, Jaggs MPR. 1998. – BRE Guide to radon remedial measures in existing dwellings. Dwellings with cellars and basements. BRE report 343, 1998. – Sealing cracks in solid floors: a BRE guide to radon remedial measures in existing dwellings. BRE Report 239, 1993. – Positive pressurisation: BRE guide to radon remedial measures in existing dwellings. BRE report BR281, 1995.

Prevention in new building

Table A 9. National situation (question B1).

Country	Preventive measures	
Austria	15	
Belgium		
Czech Republic	210 000	Original answer: Our estimate is that in approximately 2/3 up to 3/4 of new houses the preventive measures should be applied.
Finland	60 000	
France		
Germany	1 000	
Greece		
Ireland	698 870	N.B. this is the number of dwellings built since 1998 when this law was enacted
Italy		Unknown at present
Norway		
Portugal		Only a few cases
Spain		
Sweden		
Switzerland	<5 000	
United Kingdom		Not known

Table A 10. Use of prevention methods (question B2).

Method	AT	BE	CZ	FI	FR	DE	GR	IE	IT***	NO	PT	ES	CH	UK
Passive sub-slab depressurization (SSD)	YES	YES	No	YES		YES	No	YES*	YES	YES	YES		YES	No
Active SSD	YES	YES	No	YES		YES	No	No	YES	YES	YES		YES	YES*
Radon-proof barrier, membrane below floor slab	YES	YES	No	No		YES	YES	YES	YES	No			YES	YES
Radon-proof barrier, membrane above floor slab	YES	YES	YES	No		YES	YES	YES	YES	YES	YES		YES	YES
Sealing the joint between floor slab and foundation wall with membranes	YES	?	No	YES		YES	YES	D	YES	YES			YES	YES**
Sealing pipe penetrations in structures with soil contact	YES	YES	No	YES		YES	No	D	YES	YES			YES	D
Use of water-proof concrete instead of normal concrete	YES	?	No	No		YES	YES	D	YES	No			NO	No

D = Do not know
* Fan not installed unless level found to be high
** Part of measures above
*** All the listed methods are recommended by some regional Environmental Protection Agencies; however, there is no register (at present) containing information on which methods have actually been applied.

Table A 11. Prevention methods, reduction factor (%), typical range (question B2).

	AT	BE	CZ	FI	FR	DE	GR	IE	IT	NO	PT	ES	SE	CH	UK
Passive sub-slab depressurization (SSD)		?		30–40						0–20	20–50			50	
Active SSD		?		70–90						70–95	40–70			95	
Radon-proof barrier, membrane below floor slab														50	
Radon-proof barrier, membrane above floor slab			30–70							0–90	30–60			50	50
Sealing the joint between floor slab and foundation wall with membranes										0–90				30	
Sealing pipe penetrations in structures with soil contact										0–90				50	
Use of water-proof concrete instead of normal concrete															

Table A 12. Prevention methods and potential impact on energy consumption (question B2).

Method	CZ	FI	NO	CH
Passive sub-slab depressurization (SSD)		No significant effect	Low impact (fan is normally required in cold climate)	Energy consumption not relevant (ECnR)
Active SSD		No significant effect if air flows are below the rated values (0.2 – 0.5 m3/h per m2 of slab)	Low impact. (Normally this is only arranged for by a cast-in sump.)	Energy consumption: ca 300 kWh for the whole heating season (Fan of 70 W, 24 h per day for 6 months)
Radon-proof barrier, membrane below floor slab			(Not recommended due to risk of drainage problems)	ECnR Membrane can be damaged during construction, unpractical
Radon-proof barrier, membrane above floor slab	No impact		Low impact	ECnR Membrane can be damaged during construction, unpractical
Sealing the joint between floor slab and foundation wall with membranes		No effect due to small air flows	Moderate positive impact	ECnR Difficult to seal everywhere
Sealing pipe penetrations in structures with soil contact		No effect due to small air flows	Moderate positive impact	ECnR Correct sealing is necessary (door with 4 sealed parts, not only 3)
Use of water-proof concrete instead of normal concrete				

Table A 13. Reduction factors and potential impact on energy consumption for other prevention methods and combinations reported (question B2).

Other methods?	**Country**	**Reduction factor (%), Typ. range**	**Potential impact on energy consumption**
Double radon-proof membrane, above floor slab combined with depressurization of the space between the membranes	GER		
Arrangement for sub-slab or crawl space ventilation with exhaust air from house	NOR	70–95	Low impact. (Normally this is only arranged for by a cast-in sump or other methods.)
Passive ventilation under suspended concrete floor	UK	50	
Building a crawl space	POR	70–90	
Detailed radon risk maps	POR	D	
Combinations of methods above	**Country**	**Reduction factor (%), Typ. range**	**Potential impact on energy consumption**
Radon-proof membrane above floor slab + active or passive sub-slab ventilation	CZE	40–80	Minimal
Radon-proof membrane above floor slab + active or passive floor air gap ventilation	CZE	D	Minimal
Passive SSD & sealing the joint between floor slab and foundation wall with bitumen felt	FIN	40–60	No significant effect
In high radon areas a Radon-proof barrier, membrane below floor slab and a Passive sub-slab depressurization (SSD) is installed.	IRL	D	

D = Do not know

Table A 14. References (question B3).

Country	B3 References, Guides for radon prevention in new buildings, brochures, research reports, website links, other relevant documents
Austria	– ICS 13.280 Radon – Part 2: Technical precautionary measures in the case of buildings. (In German) – Brochure "Radonbelastung in Oesterreich". (In German)
Belgium	– Le Radon et votre habitation: méthodes de remédiation et de prévention. AFCN. (30 pp.) – Le radon dans les habitations: mesures préventives et curatives – Note d'information technique 211, Centre Scientifique et Technique de la Construction; 1999. – *www.fanc.fgov.be* – *www.ibes.be/radon* – *www.ecoterra.be*
Czech Republic	– ČSN 73 0601 Protection of buildings against radon from the soil. (Czech technical standard) – Jiránek M, Hůlka J. Applicability of various insulating materials for radon barriers. The Science of the Total Environment 2001; 272: 79–84. – Jiránek M. Forms of sub-slab depressurization systems used in the Czech Republic. In: Radon investigations in the Czech Republic X. 2004 Sep 15–18; Praha, Czech Republic. p. 119–125. – Jiránek M, Svoboda Z. Numerical modelling as a tool for optimisation of sub-slab depressurisation systems design. Building and Environment 2007; 42: 1994–2003. – Jiránek M, Fronka A. New technique for the determination of radon diffusion coefficient in radon-proof membranes. Radiation Protection Dosimetry 2008; 130 (1): 22–25. DOI:10.1093/rpd/ncn121 – Jiránek M, Svoboda Z. Transient radon diffusion through radon-proof membranes: A new technique for more precise determination of the radon diffusion coefficient. Building and Environment 2009; 44 (6): 1318–1327. DOI:10.1016/j.buildenv.2008.09.017
Finland	Guides 1. Radon resistant new construction. RT-Building File, RT 81-10791. Helsinki: Building Information Ltd.; 2003. (16 pp., in Finnish) 2. National Building Code of Finland (Ministry of the Environment) – B3 Foundations (unofficial English translation available), Regulations and guidelines 2004 – D2 Indoor climate and ventilation of buildings (unofficial English translation available), Regulations and guidelines 2003 Research reports 1. Arvela H, Reisbacka H, Keränen P. Radon prevention and mitigation in Finland: Guidance and practices. In: Proceedings of the American Association of Radon Scientists and Technologists AARST 2008 International Symposium. 2008 Sep 14–17; Las Vegas NV, USA 2. Keränen P, Arvela H. Radon resistant construction in Finland in 2007. In: Nordic Society for Radiation Protection – NSFS. Proceedings of the NSFS XV conference in Ålesund Norway, 26–30 of May 2008. StrålevernRapport 2008:13. Østerås: Norwegian Radiation Protection Authority; 2008. p. 125–129. 3. Arvela H, Bergman J, Yrjölä R, Kurnitski J, Matilainen M, Järvinen P. Developments in radon-safe building in Finland. Radioactivity in the Environment 2005; 7: 618–623. 4. Arvela H, Bergman J, Yrjölä R, Kurnitski J, Jokiranta K, Matilainen M, Järvinen P. Radon-safe foundation, moisture prevention and air exchange in a healthy building. SYTTY Results. Publications of the Finnish Research Programme on Environmental Health – SYTTY 1/2002. Kuopio; 2002.p. 53–57. 5. Arvela H. Experiences in radon-safe building in Finland. The Science of the Total Environment 2001; 272 (1–3): 169–174. 6. Arvela H, Kettunen A-V, Kurnitski J, Jokiranta K. Review on radon-safe building in Finland. In: Proceedings of Healthy Buildings 2000. 2000; Espoo, Finland. 7. Voutilainen A, Vesterbacka K, Arvela H. Finnish practice in building radon-safe houses – a survey for municipal authorities. STUK-A160. Helsinki: Radiation and Nuclear Safety Authority; 1998. (42 pp., in Finnish, abstract in English) 8. Ravea T, Arvela H. Radon prevention in new building in Finland. STUK-A137. Helsinki: Radiation and Nuclear Safety Authority; 1997. (45 pp., in Finnish) Website links 1. *www.rakennustieto.fi* > Products and services > Information Files 2. *www.ymparisto.fi* (The National Building Code of Finland, Ministry of the Environment) 3. *www.stuk.fi* 4. *www.radon.fi*
France	– Le radon dans les bâtiments. Guide pour la remédiation dans les constructions existantes et la prévention dans les constructions neuves. Guide technique CSTB, juillet 2008. (In French) *ese.cstb.fr/radon*
Germany	Radon-Handbuch Deutschland *www.bfs.de/en/ion/radon*

Table A 14. Continued.

Country	B3 References, Guides for radon prevention in new buildings, brochures, research reports, website links, other relevant documents
Greece	– Technical Chamber of Greece – COMMISSION RECOMMENDATION of 21 February 1990 on the protection of the public against indoor exposure to radon. 90/143/Euratom.
Ireland	Building Regulations 1997, Technical Guidance Document C *www.rpii.ie/Documents/Building-Regulations-1997---Tech-Guidance-Doc-C.aspx*, which states non complex buildings of normal design and construction, install a fully sealed membrane of low permeability over the entire footprint of the building and a potential means of extracting Radon from the substructure such as a standby sumps with connecting pipe work or other appropriate certified systems should be provided.
Italy	Linee Guida su azioni preventive nei nuovi edifici (Guidelines for radon prevention in new buildings) (in Italian only). *This document has been produced in the framework of the Italian National Radon Programme and it is going to be published.*
Norway	Byggforsk: Sikring mot radon ved nybygging. Byggdetaljer 2–2006
Portugal	*www.dct.uc.pt/lrn*
Spain	

Switzerland	– Website: *www.ch-radon.ch* (in French, German, Italian, English)
	– "Recommendations radon risk level (in French)": *www.ch-radon.ch*, in the menu on the right side
	– Website (chapter "documentation" in the menu on the right side):
	  – Swiss radon handbook (in French, German, Italian, English)
	  – Information booklets (in French, German and Italian)
	– Website (chapter "documentation" in the menu on the right side, click on "legal foundation"):
	  – Ordinance on radiation protection (in French, German, Italian, English)
	– World radon solutions database: *www.worldradonsolutions.info/*

United Kingdom	Radon: protective measures for new buildings. BRE report BR211, 2007.

Table A 15. Additional information (question C) and other comments.

Country	C Additional information and other comments
Austria	(In B2 Prevention) methods are recommended (usually in combination), but there has been no follow-up to check whether the methods were actually implemented and what impact they have on radon and energy.
Belgium	
Czech Republic	(There is a limit of) 1 000 Bq/m^3 for gaining the state financial grants up to the 5 600,- EUR for remediation.
Finland	In Finland, renewal of regulations of action level for radon remediation is in preparation (expected 200 Bq/m^3 for both existing and new buildings).
France	– This action level (for radon remediation) is planned to be applied in France in a next future – Remark: data (reduction factors for remediation) in this table are from French public buildings and not dwellings – In France, current regulation exists for some public buildings (mainly schools) and some underground activities – A future regulation should be adopted for existing dwelling (writing texts under way). For new building, it is plan but with no calendar
Germany	Remark: Voluntary action level (for radon remediation)!
Greece	
Ireland	– (In A2 reduction factors of remediation methods:) Don't know; Please Ref: High radon concentrations in a house near Castleisland, County Kerry (Ireland)—identification, remediation and post-remediation Organo et al, 2004 (attached to this email). – (In B2 radon prevention method passive SSD): ~~Passive~~ "Standby" Installed but has no effect until activated with a fan. Potential means of radon evacuation standby. This method is required in Ireland. – (In B2 Prevention) In high radon areas a Radon proof barrier, membrane below floor slab and a Passive sub-slab depressurization (SSD)2 is installed. – Please note that the RPII does not carry out this work in Ireland it is mainly carried out by builders and remediation companies. Please follow this link to the list of remediation companies we offer to our customers who have found high levels. *www.rpii.ie/getdoc/230c4c9f-2bba-46d4-bf68-56e63a60b91c/Remediation-Companies.aspx*
Italy	– (In A1.1): In Italy there is no action level for existing dwellings, at present – (In A2, method Improving mechanical ventilation in living spaces): 20% – 95% (taking care to avoid depressurization in the room) – (In A2, method Installation of a new mechanical supply and exhaust ventilation system with heat recovery): Yes (but efficiency of heat recovery is questionable) – (In A2, method House pressurization): Yes (rarely and for single rooms only) – (In A2, method Reducing under-pressure in the house): Yes (avoiding extractor fan), but In combination with other methods. – (In A2, method Sealing entry routes): Yes (but in combination with other methods) – (In B1.1): In Italy there is no target level for new buildings, at present – (In B1.3): Unknown at present (this information will be collected in near future) – The Scientific Committee of the Italian National Radon Programme recommended in 2009 that preventive measures against radon should be required for every new building. – In some regions or municipalities, some preventive measures are already required for new buildings, generally referring to the above recommendation.
Norway	For new housing: these limits (action levels for radon remediation) are under review to become legally binding
Portugal	
Spain	– (In A1) No action level in the country. – (In A2) No remedial action for general population. Research activities in a pilot house carried out by our university.
Switzerland	A radon action plan will be presented to the Federal council until the end of 2010. The strategy is focused on the prescription for new buildings and the synergies between radon and energy mitigation.
United Kingdom	

(This table includes information from Text box C and any additional comments elsewhere in the questionnaire.)

APPENDIX 2: ORIGINAL QUESTIONNAIRE

RADPAR WP 6 - Questionnaire
Assessment of radon control technologies

Once completed, please return this questionnaire to
bernard.collignan@cstb.fr

Filled in by:	
Country:	E_mail:
Organisation:	
Date:	

WP 6.1.1: Assessment of current techniques/technologies used to achieve a reduction of indoor radon concentrations in existing and new houses

A. Remediation of existing dwellings

A1 National situation

1. Action level(s) for radon remediation in your country: _____________ Bq/m^3

   If you have more than one level, please give details here:

2. Number of dwellings

	In low-rise residential buildings[1]	In apartment buildings
1. Estimated number of dwellings in your country		
2. Estimated number of dwellings exceeding the action level(s)		
3. Estimated number of dwellings already remediated		

[1] Low rise residential buildings: detached, semi-detached and row/terrace houses.

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(Please note that only questions related to WP 6.1.1 and to this report (pages 1 – 4) are included here; the rest of the questionnaire concerned WP 6.1.2, WP 6.2 and WP 6.3.)

RADPAR WP 6 - Questionnaire
Assessment of radon control technologies

A2 Remediation methods

Answer in all cases YES / NO / Don't know. In addition, fill in reduction factor in radon concentration (typical range and max) and any information on the potential impact on the energy consumption of the dwelling, if available. A directive list of methods has been given, but you may also change and add titles.

Method	**Used? (Yes/No)**	**Reduction factor (%)**		**Potential impact on energy consumption**
		Typ. range	Max	Any qualitative (or quantitative) information[1]
Sub-slab depressurization				
Improving natural ventilation in living spaces				
Improving mechanical ventilation in living spaces				
Replacing the existing natural room air ventilation by a mechanical exhaust ventilation				
Installation of a new mechanical supply and exhaust ventilation with heat recovery system				
House pressurization, (higher pressure indoors than in the soil under the floor)				
Improving ventilation in cellar				
Decreasing under-pressure in the house				
Sealing entry routes				
Improving crawl space ventilation				
Radon well (soil ventilation, outside the house)				
Soil ventilation through existing drainage piping outside the footings				
Other methods?				
Combinations of methods above[2]				

[1] For example, cooling (or warming) of sub-slab soil and floor slab, or energy losses due to increased ventilation, or energy savings due to improved ventilation strategy.
[2] You may add here typical examples of combinations.

RADPAR WP 6 - Questionnaire
Assessment of radon control technologies

A3 References

Guides for mitigation , brochures, research reports, website links, other relevant documents

B Prevention in new building

B1 National situation

1. Target level for radon in new building ____________ Bq/m^3
2. This level is: mandatory ☐ recommendation ☐
3. Estimate on the number of houses where preventive measures have been taken

____

B2 Prevention methods

List the prevention methods used in new building, and explain those briefly. A directive list of methods has been given, but you may also change and add the titles. Estimate reduction in radon concentration compared with a without-prevention situation.

Method	**Used? (Yes/No)**	**Reduction factor (%)** Typ. range	Max	**Potential impact on energy consumption** Any qualitative (or quantitative) information[1]
Passive sub-slab depressurization (SSD)[2]				
Active SSD[3]				
Radon proof insulation, membrane below floor slab				
Radon proof insulation, membrane above floor slab				
Sealing the joint of floor slab and foundation wall using membranes				
Sealing the lead-throughs in structures with soil contact				
Use of water proof concrete instead of normal concrete				
Other methods?				

RADPAR WP 6 - Questionnaire

Assessment of radon control technologies

Combinations of methods above				

[1] For example, cooling (or warming) of sub-slab soil and floor slab, or energy losses due to increased ventilation, or energy savings due to improved ventilation strategy.
[2] Vent pipe from sub-slab soil to the roof.
[3] Fan installed in the vent pipe.

B3 References

Guides for radon prevention in new buildings , brochures, research reports, website links, other relevant documents

C Additional information

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