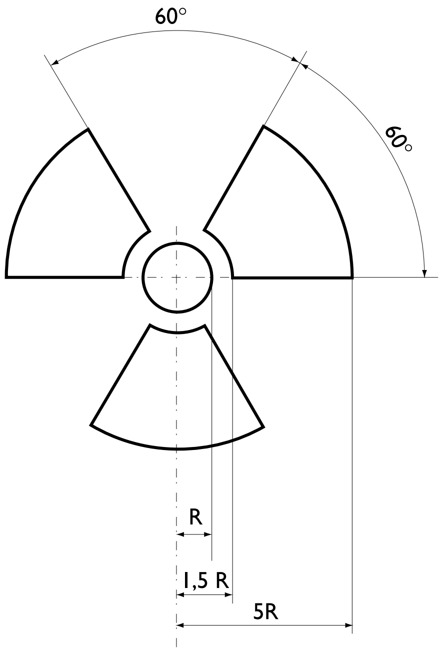
Naturally Occurring Radioactivity in the Nordic Countries – Recommendations

The Radiation Protection Authorities
in Denmark, Finland, Iceland, Norway and Sweden

2000

Naturally Occurring Radioactivity in the Nordic Countries – Recommendations



The Radiation Protection Authorities
in Denmark, Finland, Iceland, Norway and Sweden

2000

ISBN 91-89230-00-0

Preface

In the publication “Naturally Occurring Radiation in the Nordic Countries – Recommendations” published in 1986 the radiation protection authorities in Denmark, Finland, Iceland, Norway and Sweden gave radiation protection recommendations for natural radiation in the Nordic countries.

The exposure of the populations in the Nordic countries to natural radiation sources is among the highest in the world and much effort has been devoted during the last 10 to 20 years to characterising, assessing and, where feasible, to reducing these exposures. The exposure of workers to natural radiation sources has also been an important area of work in the same period.

During this period the international recommendations on radiation protection policy have been further developed with ICRP Publication 60: “1990 Recommendations of the International Commission on Radiological Protection”, and ICRP Publication 65: “Protection Against Radon-222 at Home and at Work”.

The European Basic Safety Standards Directive from 1996 (96/29/EURATOM), which is based on the ICRP recommendations, differs from the earlier versions in that special provisions have been laid down concerning exposure to natural radiation sources. As Denmark, Finland and Sweden are members of European Union and the EFTA-countries (Iceland and Norway) have close co-operation with the EU, the practical implementation of the EU-BSS will play an important role in all the Nordic countries.

In November 1998, a new Drinking Water Directive, 98/83/EC, was adopted. The directive also includes radioactivity in drinking water, excluding potassium-40, radon and radon decay products.

Altogether this means that the Nordic recommendations from 1986 for natural radiation needed to be updated. The Nordic Radiation Protection Authorities therefore decided to set up a working group with the aim of revising the recommendations from 1986. The new revised recommendations will, as before, only deal with the components of the exposure to natural radiation that are amenable to control and which can cause doses that are not trivial. Control of exposure of aircrew to cosmic radiation is, however, dealt with in a separate recommendation prepared together with the Nordic civil aviation authorities.

The Nordic Radiation Protection Authorities approved the revised recommendations at a meeting in Copenhagen, March 2000, and adopted them for publication in the Flag-book series.

The recommendations are written primarily for other authorities and policy-makers in the Nordic countries but they may also be of interest to radiation protection professionals and authorities outside the Nordic countries and to individuals with some basic knowledge of natural radioactivity.

The new recommendations may serve as a basis for more formal rules, regulations and recommendations within each country if this is deemed necessary. However, no attempt has been made to formulate identical regulations for all the five Nordic countries since the exposure levels from natural sources, methods of application and the legal frameworks differ between the countries.

Members in the working group have been:

G. Åkerblom (chairman), Statens strålskyddsinstitut, SSI
(Swedish Radiation Protection Institute),
Stockholm, Sweden

L. Mjönes (secretary), Statens strålskyddsinstitut, SSI
(Swedish Radiation Protection Institute),
Stockholm, Sweden

M. Annanmäki, Säteilyturvakeskus, STUK
(Radiation and Nuclear Safety Authority),
Helsinki, Finland

S. Magnusson, Geislavarnir rikisins
(Icelandic Radiation Protection Institute),
Reykjavik, Iceland

T. Strand, Statens strålevern
(Norwegian Radiation Protection Authority),
Oslo, Norway

K. Ulbak, Statens Institut for Strålehygiene, SIS
(National Institute of Radiation Hygiene),
Copenhagen, Denmark

List of Contents

Naturally Occurring Radioactivity in the Nordic Countries – Recommendations

Summary of recommendations

1. Radon in indoor air – recommendations

Radon in existing dwellings

- **The recommended investigation level for radon in existing dwellings is 200 Bq/m^3.**

- **The recommended action level for radon in existing dwellings is 400 Bq/m^3.**

  Remedial measures in dwellings should be considered when the annual mean radon concentration in the living area exceeds 200 Bq/m^3. In the range between 200 and 400 Bq/m^3 simple, low cost measures are recommended. At levels exceeding 400 Bq/m^3, remedial measures should be undertaken with the aim of bringing the radon level below 200 Bq/m^3. Remedial measures should be cost-effective and based on well-proven techniques.

  It is recommended that the classification of radon-prone areas is based on measurements in a representative sample of the building stock combined with measurements, geological data and information on building construction.

Radon in workplaces

- **The recommended action level for radon in aboveground workplaces is 400 Bq/m^3.**

- **An action level for radon in underground workplaces within the interval 400 – 1,500 Bq/m^3, expressed as average activity concentration during the working hours, is recommended.**

If it is not possible to reduce the radon level below the action level, the workplace should be treated in the same way as a practice. This would imply the application of dose limits.

Remedial measures in aboveground workplaces should be considered when the annual mean radon concentration exceeds 400 Bq/m^3. Authorities may take into consideration the annual occupancy.

Radon in new buildings

■ **The recommended upper level for radon in new buildings is 200 Bq/m^3.**

New buildings include dwellings and aboveground workplaces and other buildings utilised more than temporarily. New buildings should be planned and constructed in such a way that the annual average radon concentration will be as low as reasonably achievable.

2. Natural radioactivity in drinking water – recommendations

Radon in drinking water

■ **The recommended exemption level for radon in drinking water is 100 Bq/l.**

■ **The recommended upper level for radon in drinking water is 1,000 Bq/l.**

Long-lived radionuclides in drinking water

- **The recommended upper level, expressed as annual effective dose, for exposure to long-lived radionuclides in drinking water is 1 mSv.**

  National authorities may also select an upper level below 1 mSv per year if they judge that it is desirable and will not lead to an unmanageable number of wells to be mitigated.

  It is recommended that the water from a drilled well should be analysed for radon when a new well is taken into use in case the bedrock consists of igneous rocks.

3. Exposure from gamma radiation – recommendations

Exposure to gamma radiation in buildings and at often used places outdoors

- **The recommended upper level for exposure to external gamma radiation in existing buildings, expressed as ambient dose equivalent rate, is 1 μSv per hour.**

- **The recommended upper level for exposure to external gamma radiation in new buildings, expressed as ambient dose equivalent rate, is 0.5 μSv per hour.**

- **The recommended investigation level for exposure to gamma radiation at often used places outdoors, e.g. playgrounds, expressed as ambient dose equivalent rate, is 1 μSv per hour.**

Building materials for new constructions

- **The recommended exemption level for the activity concentration of radium-226 in building materials for new constructions as a source of indoor radon is 100 Bq per kg.**

- **The recommended upper level for the activity concentration of radium-226 in building materials for new constructions as a source of indoor radon is 200 Bq per kg.**

  If the upper level is exceeded for a particular material, an assessment of the contribution of the material to the indoor radon concentration should be made. The assessment should be based on a realistic use of the material and take into consideration the amount of the material which is used and in what parts of the building it is used.

- **The recommended exemption level for the activity concentrations in building materials as a source for gamma radiation in new constructions should be determined by the inequality**

$$m_\gamma < 1$$

- **The recommended upper level for the activity concentration in building materials as a source for gamma radiation in new constructions should be determined by the inequality**

$$m_\gamma < 2$$

where $m_\gamma = C_K/3000 + C_{Ra}/300 + C_{Th}/200$ and C_K is the concentration of potassium-40, C_{Ra} the concentration of radium-226 and C_{Th} the concentration of thorium-232, all in Bq/kg.

If the recommended levels are exceeded for a particular material, an assessment of the contribution of the material to the indoor gamma radiation level should be made. The assessment should be based on a realistic use of the material and take into consideration the amount in which the material is used and in what parts of the building it is used.

1. Basic concepts (definitions)

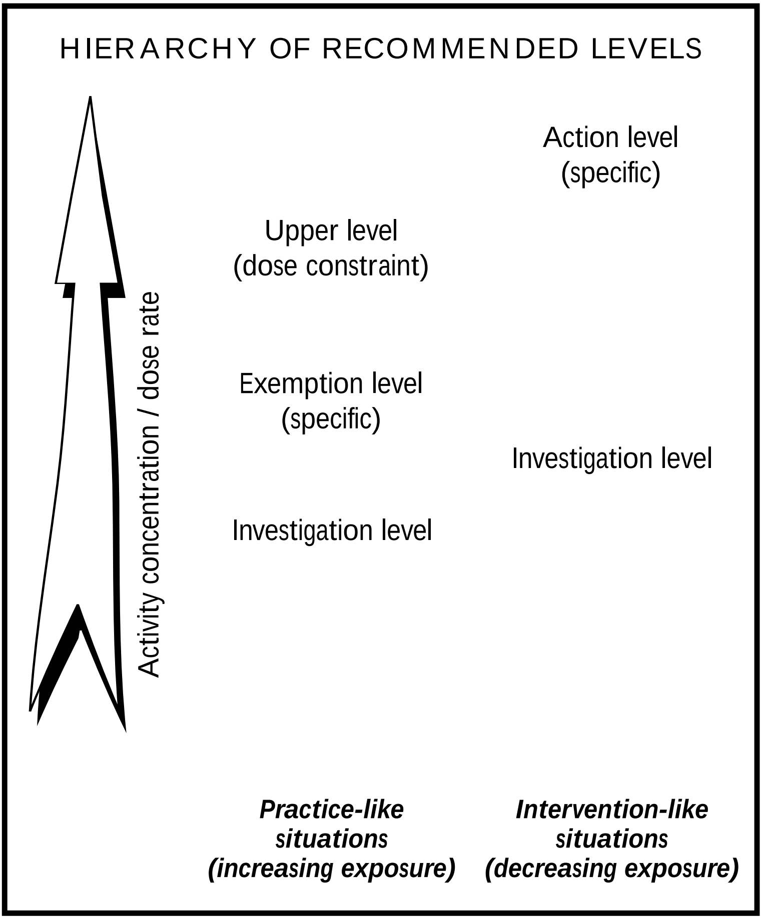


Figure 1: Hierarchy of recommended levels

Practice-like situations. These are situations in which human activities can increase the overall exposure to natural radiation and where operational or regulatory controls could optimise and limit the future exposure. Examples are radon in new dwellings, drilling of new water wells, introducing a new type of building material on the market.

Intervention-like situations. Situations where the sources of exposure and the exposure pathways are already present and the only type of possible action is intervention to reduce the exposure. Examples are radon in existing dwellings, existing water wells with enhanced levels of natural radionuclides, building materials in an existing house.

Action level. The level of activity concentration or dose rate above which remedial action or protective actions should be carried out to reduce exposure to individuals. Action levels are used in an intervention-like situation. If remedial or protective action is not successful or they are not feasible the future exposure conditions should be defined, e.g. that the exposure at a workplace to the specified source of natural radiation is treated as a practice.

Exemption level. The level of activity concentration or dose rate below which no specific exposure assessment or exposure control needs to be undertaken for a specified natural radiation source.

Investigation level. The level of activity concentration or dose rate above which assessment of the exposure conditions of a specified type of natural radiation source should be undertaken. The investigation level can be used both in a practice-like situation (e.g. a new building material) and in an intervention-like situation (e.g. ground water). The purpose of the assessment should be to determine or advise whether any form of exposure control (recommendation, establishment of a specific exemption level, restriction in use etc.) should be introduced for that source. In these recommendations, investigation levels are given only as source-related levels. In this way an investigation level can also be regarded as a level under which unrestricted use of a source is acceptable under all normal circumstances.

Upper level (dose constraint). A prospective and source-related restriction on the individual dose delivered by a specified natural radiation source which serves as a bound in the optimisation of protection of that source. The upper level should be established or recommended by the national radiation protection authority, if deemed necessary, on the basis of the highest risk that is considered acceptable to individuals under the exposure conditions considered. It is believed that the future average exposure from the specified natural radiation source will be well below the recommended upper level and that the actual exposures will be kept as low as reasonably achievable (ALARA). The upper level should be an aid for relevant authorities in establishing regulations, standards, codes of practices etc. for the circumstances under which exposure may occur. The dose constraint should not necessarily be a legal limit in itself.

2. Dosimetric quantities, exposure models and dose calculations

Unless otherwise stated, the following dosimetric quantities and exposure models are used in the overview of natural activity in the Nordic countries (Chapter 4) and in the recommendations (Chapters 5–7).

2.1. Gamma radiation

Gamma levels indoors and outdoors are given in the quantity ambient dose equivalent rate [dH*(10)/dt]. The unit for *ambient dose equivalent rate* is usually nSv/h or μSv/h. Observe that for photons, the operational (measurable) quantity ambient dose equivalent always overestimates the protection quantity effective dose, E. The relationship between the effective dose, E, and the ambient dose equivalent, H*(10), for natural radiation is approximately:

$$E = H^*(10) \cdot 0.6 \text{ (1 MeV, ISO geometry)}$$

as can be found in ICRU Report 57 (ICRU 1998).

If measurement data are presented which were originally given in other quantities, the following conversion coefficients to ambient dose equivalent rate have been used (it has been assumed that the absorbed dose in air is equivalent to air kerma free in air, K_a) (ICRU 1998):

From exposure rate	*0.010 μSv/h per μR/h*
From absorbed dose rate in air	*1.17 μSv/h per μGy/h (1 MeV)*

The conversion factor used by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 1993) from absorbed dose in air to effective dose, E, is 0.7 Sv/Gy.

For calculations of the gamma radiation level at 1 m above the ground from the decay series ^{238}U, ^{232}Th and for ^{40}K, in equilibrium and distributed homogeneously in the ground, the relationships in Table 2.1.1 have been used (IAEA 1990).

Nuclides	Ambient dose equivalent rate, nSv/h per Bq/kg
Uranium-238 series	0.531
Thorium-232 series	0.718
Potassium-40	0.049

Table 2.1.1. Ambient dose equivalent rate at 1 m above the ground from the decay series ^{238}U, ^{232}Th and for ^{40}K (IAEA 1990).

2.2. Radon in indoor air

When exposure to radon (and radon progeny) is to be compared to the exposure from other radiation sources it is necessary to estimate the effective dose per unit radon gas exposure. In the past this has predominantly been done by using the dosimetric evaluation of the absorbed dose to basal cells of the bronchial epithelium and applying the ICRP convention for calculating effective dose (effective dose equivalent). For exposure in dwellings the range of such evaluations has been 0.02–0.09 mSv per year per Bq/m^3 as average exposure during the year (equilibrium factor 0.4) with a central estimate of 0.05 mSv per year per Bq/m^3. In the Nordic recommendations from 1986 (Nordic 1986), a value of 0.037 mSv per year per Bq/m^3 based on the UNSCEAR 1982 Report was used for exposure of the public in dwellings (UNSCEAR 1982).

As an alternative to the dosimetric approach the ICRP has, in Publication 65 from 1993, derived a conversion convention for radon exposure based on equality of detriment from epidemiological determinations (miners) (ICRP 65, 1993). This gives a dose coefficient of 0.021 mSv per year per Bq/m^3 as the average exposure during the year (equilibrium factor 0.4) for public exposure. The difference between the dosimetric approach and the epidemiological approach is a factor of about 2.5. Since the whole issue is very complex this is not a very large difference.

In the following recommendations the ICRP conversion convention has been used for both dwellings and workplaces:

Dwellings: 0.021 mSv per year per Bq/m^3 (average over 8,760 hours, equilibrium factor 0.4)

Workplaces: 0.0063 mSv per year per Bq/m^3 (average over 2,000 hours, equilibrium factor 0.4).

2.3. Natural radioactivity in drinking water

Studies of radon and other inert gases have shown that they are absorbed from the gastrointestinal tract and readily eliminated through the lungs. For ingested radon from drinking water the stomach is the organ of primary concern. It should be kept in mind that the dose estimations for radon in drinking water are afflicted with considerable uncertainties. Estimates of the annual committed effective dose to an adult from ingestion of water containing 1,000 Bq/l vary from 0.2 to 1.8 mSv, depending on the annual water consumption and the range of conversion factors used. It is important to stress that the greatest risk associated with radon in drinking water is normally the inhalation of the radon that is released from the water into the indoor air. In 1993, it was estimated that the total (inhalation and ingestion) life-time risk posed by exposure to radon in drinking water at 1 Bq/m^3 was $1.4 \cdot 10^{-8}$. Of that risk, $0.2 \cdot 10^{-8}$ was associated with ingestion and $1.2 \cdot 10^{-8}$ with inhalation (SSI i 94–06).

The transfer coefficient from radon in water to indoor air, i.e. the average fraction of the radon in the water that is transferred into the indoor air, has been estimated to be $1.0 \cdot 10^{-4}$ (NRC 1999). This means that if the average radon concentration in the drinking water is 1,000 Bq/l, the average contribution to the indoor air would be 100 Bq/m^3.

In its report of 1993, the UNSCEAR estimated that the committed effective dose from ingestion of radon in water is 10 nSv per Bq. The doses to infants and children were estimated to be several times higher, for infants more than ten times higher, than for adults. The annual intake of tap water was estimated to be about 100, 75 and 50 litres per year for infants, children and adults. If the proportions of these groups in the population are assumed to be 5 percent, 30 percent and 65 percent, the weighted annual consumption would be 60 litres. The annual population-weighted effective dose from ingestion of drinking water with 1,000 Bq/l radon would then be 1 mSv (UNSCEAR 1993).

In 1998, a National Research Council, NRC, committee in the United States presented their risk estimation for radon in drinking water (NRC 1999). The committee estimated the committed effective dose to the stomach wall from radon in drinking water to be 3.5 nSv per Bq. The NRC committee was of the opinion that there is not sufficient scientific information to allow separate dose estimations for different populations such as infants, children and adults (NRC 1999). Using the NRC committee dose conversion factor, the population-weighted average annual effective dose from ingestion of drinking water with 1,000 Bq/l radon would be 0.2 mSv.

When radon is removed from drinking water using aeration, the short-lived decay products of radon will remain in the cleaned water for a short time after the aeration. A Swedish pilot study indicates that the short-lived radon progeny in some cases follow the water to the tap for consumption to such an extent that the problem should be considered. However, this study also shows that the effective dose from the short-lived radon progeny is always lower than the dose from the radon would have been if no aeration had taken place (Swedjemark and Lindén 1998). The NRC committee, however, concluded in their report that radon progeny cannot diffuse into the stomach wall and that the alpha particles emitted cannot reach the sensitive stem cells.

When calculating the dose due to radioactivity in drinking water, it is normally assumed that the daily water consumption is 2.2 litres (ICRP 23 1975) but there are great individual variations. In Sweden, the daily consumption of water is considerably lower than that assumed by the ICRP and this has a significant effect on the dose calculations (Swedjemark and Lindén 1998).

The derived activity concentrations for long-lived radionuclides in drinking water corresponding to an annual effective dose of 1 mSv are presented in Table 2.3.1.

Nuclide	Activity concentration, Bq/l (Child 1 y)	Activity concentration, Bq/l (Child 10 y)	Activity concentration, Bq/l (Adult)
U-238	3.7	18	28
U-234	3.4	17	26
Ra-228	0.04	0.32	1.8
Ra-226	0.27	1.6	4.5
Pb-210	0.15	0.66	1.8
Po-210	0.05	0.50	1.0

Table 2.3.1. Derived activity concentrations for long-lived radionuclides in drinking water corresponding to an annual effective dose of 1 mSv.

The activity concentrations of nuclides presented in the table cause an effective dose of 1 mSv when 2.2 litres of water is used daily throughout one year. The conversion factors are adopted from EU Basic Safety Standards Directive from 1996 (EC 1996). If the conversion factors from UNSCEAR 1993 are used, the activity concentration for radon in water that would give an annual population-weighted effective dose of 1 mSv would be about 1,000 Bq/l. Using the NRC committee conversion factor about 5,000 Bq/l would be needed for a dose of 1 mSv.

2.4. Building materials

For the calculation of gamma radiation levels indoors for building materials containing naturally occurring radionuclides, the factors in Table 2.4.1 have been used (Markkanen 1995).

Table 2.4.1. Ambient dose equivalent rate for the decay series ^{238}U, ^{232}Th and for ^{40}K for a room with the dimensions 5 m x 4 m x 2.8 m. Walls, floor and ceiling are assumed to be 20 cm thick concrete with a density of 2,320 kg per m^3 (Markkanen 1995).

Nuclides	Ambient dose equivalent rate, nSv/h per Bq/kg
Uranium-238 series	1.06
Thorium-232 series	1.24
Potassium-40	0.09

3. International recommendations and regulations

The great variability of exposures to workers and members of the public from natural radiation sources and the very high exposures to some minor or major groups hereof were identified during the last 2–3 decades. In the same period, international recommendations and regulations have been further developed to take account of this new situation. Since the evolution and the acceptability of the international recommendations has been progressing rather rapidly, it is important to note the differences in the principles, terminology and conversion factors etc. between the different recommendations and regulations. An example of this has been the changing conversion factor from the annual average radon concentration in a dwelling and the corresponding effective dose (or effective dose equivalent).

A short overview is given in this chapter of the most important recommendations regarding exposure to natural radiation sources from the International Commission on Radiological Protection (ICRP) and of the requirements in the European Basic Safety Standards Directive (EU BSS) (EC 1996) and the Drinking Water Directive (EC 1998). The EU BSS is based on the recommendations of the ICRP. Besides these recommendations and regulations one must also take note of other international recommendations and regulations such as The World Health Organisation (WHO) and the International Basic Safety Standards prepared jointly by FAO, IAEA, ILO, OECD/NEA, PAHO and WHO.

3.1. The ICRP recommendations

The latest basic recommendations on radiological protection from ICRP are given in Publication 60: "1990 Recommendations of the International Commission on Radiological Protection" (ICRP, 1991) The ICRP distinguishes between practices, where human activities increase the overall exposure to radiation, and intervention, where human activities decrease the overall exposure. The system of radiological protection recommended by the ICRP for practices is based on the following general principles (ICRP 60, paragraph 112):

(a) No practice involving exposures to radiation should be adopted unless it produces sufficient benefit to the exposed individuals or to society to offset the radiation detriment it causes. (The justification of a practice).

(b) In relation to any particular source within a practice, the magnitude of individual doses, the number of people exposed, and the likelihood of incurring exposures where these are not certain to be received should all be kept as low as reasonable achievable, economic and social factors being taken into account. This procedure should be constrained by restrictions on the doses to individuals (dose constraints), or the risks to individuals in the case of potential exposures (risk constraints), so as to limit the inequity likely to result from the inherent economic and social judgements. (The optimisation of protection).

(c) The exposures of individuals resulting from the combination of all the relevant practices should be subject to dose limits, or to some control of risk in the case of potential exposures. These are aimed at ensuring that no individual is exposed to radiation risks that are judged to be unacceptable from these practices in any normal circumstances. Not all sources are susceptible of control by action at the source and it is necessary to specify the sources to be included as relevant before selecting a dose limit. (Individual dose and risk limits).

The system of radiological protection recommended by the ICRP for intervention is based on the following general principles (ICRP 60, paragraph 113):

(a) The proposed intervention should do more good than harm, i.e. the reduction in detriment resulting from the reduction in dose should be sufficient to justify the harm and the costs, including social costs, of the intervention.

(b) The form, scale, and duration of the intervention should be optimised so that the net benefit of the reduction of dose, i.e. the benefit of the reduction in radiation detriment, less the detriment associated with the intervention, should be maximised.

The ICRP gives the following specific recommendations on the exclusion of occupational exposure to natural radiation sources (ICRP 60, paragraph 135):

> Of the components of exposure to natural sources, those due to potassium-40 in the body, cosmic radiation at ground level, and radionuclides in the earth's crust are all outside any reasonable scope of control (of the operating management). Only radon in workplaces and work with materials containing natural radionuclides can reasonably be regarded as the responsibility of the operating management. Furthermore, there is some exposure to radon in all workplaces, and it is important not to require the use of a formal system of separate decisions to exempt each individual workplace where controls are not needed. They should be excluded from the control of occupational exposure by some general system. Considerable knowledge and judgement is needed to define such a system. The Commission recommends that exposure to radon and the handling of materials containing traces of natural radionuclides should be regarded as excluded from occupational exposure and treated separately, unless the relevant regulatory agency has ruled otherwise, either in a defined geographical area or for defined practices.

To provide some practical guidance, the Commission recommends that there should be a requirement to include exposures to natural sources as part of occupational exposure only in the following cases (ICRP 60, paragraph 136):

(a) Operations in workplaces where the regulatory agency has declared that radon needs attention and has identified the relevant workplaces.

(b) Operations with and storage of materials not usually regarded as radioactive, but which contain significant traces of natural radionuclides and which have been identified by the regulatory agency.

(c) Operation of jet aircraft.

(d) Space flight.

Radon in dwellings is dealt with by the ICRP in the context of intervention. The ICRP recommends the use of action levels for the initiation of intervention (ICRP 60, paragraph S 48):

> ... to help in deciding when to require or advise remedial action in existing dwellings. The choice of action level is complex, depending not only on the level of exposure, but also on the likely scale of action, which has economic implications for the community and for individuals.
>
> ... the best choice of an action level may well be that level which defines a significant, but not unmanageable, number of houses in need of remedial work. It is then not to be expected that the same action level will be appropriate in all countries.

More specific recommendations regarding radon in workplaces and in dwellings are given by the ICRP in Publication 65 (1993): "Protection Against Radon-222 at Home and at Work".

For radon in dwellings, the ICRP gives the following specific recommendation regarding deciding on the value of an action level and the implementations of this in practice (ICRP 65, paragraphs 70–73):

> It is clear that elevated levels of radon do occur in some dwellings, that it is possible to identify the conditions under which they arise, that remedial and preventive measures are usually simple and of moderate cost, and that there are appreciable risks attendant on elevated exposures. Intervention is therefore feasible. The main matter is the determination of the action level at which intervention should be taken.
>
> ... action level relates to the annual mean concentration of radon in a building. It is important that the action taken should be intended to produce substantial reduction in radon exposures. It is not sufficient to adopt marginal improvements aimed only at reducing the radon concentrations to a value just below the action level. Once interventions are decided, the degree of

> the intervention should be optimised.
>
> It seems clear that some remedial measures against radon in dwellings are almost always justified above a continued annual effective dose of 10 mSv. For simple remedial measures, a somewhat lower figure could be considered, but a reduction by a factor of five or ten would reduce the action level to a value below the dose from natural background sources. The choice of action level for annual effective dose is thus limited to the range of about 3–10 mSv. The Commission recommends that the action level should be set within this range by the appropriate authorities.
>
> The corresponding rounded value of radon concentration is about 200–600 Bq/m^3, with an annual occupancy of 7,000 hours and an equilibrium factor of 0.4. ...

For radon at workplaces the ICRP gives the following specific recommendation regarding deciding on the value of an action level and the implementations of this in practice (ICRP 65, paragraphs 86, 92–93):

> Workers who are not regarded as being occupationally exposed to radiation are usually treated in the same way as members of the public. It is then logical to adopt an action level for interventions in workplaces at the same level of effective dose as the action level for dwellings. The action levels for intervention in workplaces can be most easily derived from the range of action levels for dwellings. The resulting range (rounded) is 500–1,500 Bq/m^3.
>
> Having adopted an action level, the regulatory agency or the employer will need to determine what is to be done with a workplace where the radon concentration exceeds that level. It would seem most sensible to start by taking whatever remedial measures are necessary to reduce the radon concentration to a value well below the action level. In many buildings, there will be little difficulty in taking such measures, but this may not be so in large complex structures.
>
> Should it prove unreasonably difficult, either in all or some parts of a building or an underground workplace, to reduce the radon level below the action level, the system of radiological protection should be the same as when workers are exposed to artificial airborne activity at work. If radon concentrations vary widely in different parts of the workplace, the action level may be based on the annual time-weighted average concentration in the different parts of the workplace.

3.2. EU Basic Safety Standards Directive

In May 1996, the European Council adopted a revised European Basic Safety Standards Directive (EU BSS, Directive 96/29/Euratom laying down basic safety standards for the protection of the health of workers and the general public against the dangers from ionising radiation) (EC 1996). The EU BSS directive is based on the general recommendations in ICRP Publication 60 regarding practices and intervention. The EU BSS “shall not apply to exposure to radon in dwellings or to the natural level of radiation, i.e. to radionuclides contained in the human body, to cosmic radiation prevailing at ground level or to aboveground exposure to radionuclides present in the undisturbed earth’s crust”.

For the exposure to radon in dwellings, the European Commission published, in 1990, a specific recommendation (EC 1990). Although the dose conversion from annual average radon concentration to effective dose in the recommendation is based on earlier recommendations from the ICRP (Publication 50, 1987) the recommended action level for existing buildings (400 Bq/m^3) and the planning level for future constructions (200 Bq/m^3) are still regarded as applicable by the Commission.

The revised directive differs from the earlier versions in that special provisions have been laid down in Title VII of the EU BSS Directive (EC 1996) for exposure to natural radiation sources. Title VII of the directive applies to work activities within which the presence of natural radiation sources leads to a significant increase in the exposure of workers or members of the public, which cannot be disregarded from the radiation point of view. Member States shall identify work activities which may be of concern (Article 40). These work activities may include:

a) Work activities where workers and, where appropriate, members of the public are exposed to radon or thoron daughters or gamma radiation or any other exposure in workplaces such as spas, caves, mines, underground workplaces and aboveground workplaces in identified areas.

b) Work activities involving operations with and storage of materials, not usually regarded as radioactive but which contain naturally occurring radionuclides, causing a significant increase in the exposure of workers and, where appropriate, members of the public.

c) Work activities which lead to the production of residues not usually regarded as radioactive but which contain naturally occurring radionuclides, causing a significant increase in the exposure of members of the public and, where appropriate, workers.

d) Aircraft operation.

When Member States have declared a specific type of work activity to be of concern, appropriate means to monitor exposures shall be set up and for practice-like situations the application of radiation protection measures for practices in the EU BSS Directive (Titles III, IV, V and VIII) should be implemented totally or partially. For intervention-like situations the application of corrective measures for intervention (Title IX) in the Directive should be implemented totally or partially (EC 1996).

The EU BSS Directive gives the Member States a high degree of flexibility in implementing the articles on natural radiation sources into national legislation. More detailed guidance and recommendations on the identification of such work activities and related workplaces and on the nature of control that may then be appropriate have been prepared for the Commission by a Working Party under the Article 31 Group of Experts (Recommendations for the implementation of Title VII of the European Basic Safety Standards Directive (BSS) concerning significant increase in exposure due to natural radiation sources. Directorate-General Environment, Nuclear Safety and Civil Protection. European Commission 1997) (EC 1997).

The major part of the Working Party's detailed guidance covers radon in workplaces dealing with surveys, action levels, radon prone areas, testing and remedying existing workplaces and how to apply the normal radiation protection system if remedial measures cannot reduce the radon concentration below the action level. Regarding the setting of an action level for radon in a workplace, the recommendations note that for regulatory purposes it is desirable for the action level not to exceed the dose level at which special actions are required in the Directive to protect workers involved in normal practices, i.e. the criterion for classifying category A workers (6 mSv per year). For this reason the recommendations state that within the European Union, the action level for places of work should be set in the range 500–1,000 Bq/m^3 time averaged radon gas concentration corresponding to a range of effective doses of 3–6 mSv per year. National Authorities may, however, also select an action level below this range if they judge that this is desirable and will not lead to an impractical radon programme.

For the control of exposures of workers from materials with elevated levels of natural radionuclides (use, storage, residues), the detailed guidance notes that if the doses are less than 1 mSv per year (radon excluded) then no special precautions are required. If annual doses exceed 1 mSv the normal scheme for controlling exposures can usually be applied. However, for doses in the range 1–6 mSv per year it would be appropriate to consider whether doses could effectively be reduced and whether there is a possibility that doses increase either over time or as the result of an accident.

3.3. EU Drinking Water Directive

The Drinking Water Directive, 98/83/EC, includes a parametric value of 100 Bq/l for tritium and a "total indicative dose" of 0.1 mSv per year, excluding tritium, potassium-40, radon and radon decay products, in Annex I, Part C, Indicator parameters. The concept of "total indicative dose" is not explicitly defined in the directive, but Article 8.6 says:

> In the event of non-compliance with the parametric values or with the specifications set out in Annex I, Part C, Member States shall consider whether that non-compliance poses any risk to human health. They shall take remedial action to restore the quality of the water where that is necessary to protect human health.

EU recommendations for radon and long-lived radon decay products in drinking water are in preparation (July 2000).

4. Natural radioactivity in the Nordic countries

4.1. Introduction

The predominant part of the natural radiation in our environment and in humans is caused by the primordial radionuclides in the decay series starting with uranium-238, thorium-232, uranium-235 and potassium-40, and by cosmic radiation. The primordial radionuclides are present in bedrock, soil, building materials, water, air and in the human body. The contents of the natural radioactive substances vary widely between different rocks and soil types, due to the different ways in which they were formed. The internal radiation in the human body is caused by natural radionuclides in food, water and air. Due to a higher consumption of fish and reindeer meat, the population in Norway receives a somewhat higher internal dose than the populations in Sweden and Finland. The cosmic radiation increases with increased height above sea level.

Table 4.1.1. Estimated average effective dose to the public from natural radiation, mSv per year.

Source	Finland	Sweden	Denmark	Norway	Iceland
Gamma radiation from bedrock, soil and building materials	0.5	0.5	0.3	0.5	0.2
Radon concentrations at home and at work	2.0	1.9	1.0	1.7	0.2
Radioactive elements in the body [1)]	0.3	0.3 [2)]	0.3 [2)]	0.35	0.3
Cosmic radiation	0.3	0.3	0.3	0.3	0.3
Total	3.1	3.0	2.0	2.9	1.0

1) Including the dose from ^{210}Po.

2) According to UNSCEAR 1993.

The average radiation which normally occurs in an area is called the background radiation. The level of this radiation depends on local conditions. We always have to accept a certain level of background radiation and there is no justification for protecting ourselves against radiation at levels which are average for a country. Locally, however, the level of the natural radiation can be so high that protective measures may be justified or fully necessary. The radiation dose, which individuals or groups receive from the radiation from natural radioactive substances may also become intensified due to human intervention or people's ways of life. In such cases there may be special motivation for measures aimed at reducing the individual or collective doses. Examples of circumstances in which human activities have led to higher individual or collective doses are radon in dwellings and in mines, the use of building materials with higher than normal contents of radioactive substances, the enrichment of radioactive substances in the slag from blast furnaces and deposits in pipes used in the production of oil and gas. Increased use of water from wells drilled in rock has also led to increased radiation doses in large sections of the population due to radon and other natural radioactive substances in the water.

Since the geological and topographical conditions differ between the Nordic countries, the average doses to the public due to natural radiation are different for the Nordic countries (Table 4.1.1).

4.2. Natural radioactivity in bedrock and soil

The natural radiation to which we are exposed from bedrock, earth and water consists mainly of gamma radiation from the ground, stone surfaces and stone-based building materials and of alpha radiation from the daughter-products of radon. The contents of uranium and thorium, and therefore of their daughter products, vary considerably between, and within, rocks, often even in the same area. Locally, the uranium and thorium contents can be very high, several percent, as is the case in ores and in occurrences of uranium and thorium. Certain types of rocks commonly have higher contents of uranium and thorium than others. Examples of such rocks are certain types of granites, acidic gneiss, pegmatites, carbonatites and black shales such as alum shale, a uranium-rich Cambrian black shale which occurs in Sweden, Norway and the Danish island Bornholm. Uranium-rich granites are to be found in many and extensive areas in Finland, Sweden, and Norway. In Denmark, uranium-rich granite occurs in Bornholm. Granites and other intrusive rocks only exist at a few remote places in Iceland where the bedrock consists mainly of basic volcanic rocks. Examples of rocks with low contents of uranium and thorium are limestone, sandstone, shale and volcanics with a basic composition. Table 4.2.1 shows the activity concentrations of radium-226, thorium-232 and potassium-40 for various types of rocks in the Nordic countries.

Where the surface layers of the ground consist of soil, the intensity of the gamma radiation from the ground depends on the concentration of the radioactive substances in the soil. The same applies to the radon contents of soil air and subsoil water. To a large extent the earth cover in the Nordic countries consists of moraine produced from rock crushed by the ice-sheet that covered the land during the glacial periods. Moraines are often of local origin and they therefore reflect the contents of radioactive substances in the underlying bedrock. Gravel, sand, silt and clay are soil types, which have been transported by water and then settled. For gravel and coarse sand, the contents of radioactive substances depend on the rocks from which they originated. Sand and silt have consistently low contents of uranium and thorium since the radioactive elements have been carried away with the water. The clays have adsorbed uranium, radium and thorium from the water and they have often higher contents of these substances than sand and silt. Since the bedrock in Finland, Sweden and Norway consists to a large extent of crystalline basement rocks, the contents of uranium, radium, thorium and potassium in the earth layer is on average higher in these countries than in Denmark, where the surface layers of the rock consist entirely of Cretaceous to Tertiary sedimentary rocks; limestone, shale, sandstone, and unconsolidated layers of clay, silt and sand. An exception is the island Bornholm where the bedrock consists largely of granite. The soils in Iceland have even lower concentrations of natural radioactive elements since the bedrock there consists almost entirely of volcanic rocks with a basic composition. Table 4.2.2 shows typical activity concentrations of radium-226, thorium-232 and potassium-40 in soils and radon-222 soil air in the Nordic countries and in the Appendix Tables 1 and 2 show activity concentrations of representative Swedish and Finnish soil samples.

The gamma radiation outdoors originates from radioactive substances in the ground and from fallout from radionuclides in connection with the testing of nuclear weapons and the Chernobyl accident. The part of the gamma radiation which originates from naturally radioactive substances, depends on their concentrations in rocks and the soil cover. Because of the self-absorption in the soil cover, more than 90% of the gamma radiation above the ground originates in the uppermost 20 cm of the soil layer. The water in the pores of the soil also provides shielding from the gamma radiation, as does the vegetation cover to some extent. In the winter, if the ground is covered by snow, the radiation is reduced due to the absorption in the water of the snow. The shielding increases exponentially with increasing water content in the snow cover. If the water content corresponds to a 10 cm layer of water, the exposure rate is reduced by about 50%. The shielding effect of the air mass within a few meters from the ground is so small that it is of no significance for the exposure to a person in the area.

Table 4.2.1. Nordic rocks. Typical ranges of activity concentrations of radium-226 [1)], thorium-232 and potassium-40 (Åkerblom et al. 1988, Åkerblom 1999).

Type of rock	^{226}Ra, Bq/kg	^{232}Th, Bq/kg	^{40}K, Bq/kg
Granite, normal	20-130	20-80	620-2,400
Granite, uranium- and thorium-rich	100-500	40-350	1,200-1,900
Gneiss	25-130	20-80	620-1,900
Carbonatites	10-650	40-10,000	100-1,000
Diorite, gabbro and basic volcanic rocks	1-30	2-40	50-1,000
Sandstone and quartzite	5-60	5-40	60-1,500
Limestone and dolomite	2-30	0.5-10	<30-150
Shale	10-150	10-60	600-1,900
Alum shale	100-4,300	10-40	1,100-1,900

[1)] In the Nordic bedrock, radioactive equilibrium normally prevails between uranium-238 and radium-226 and within the thorium-232-series.

If the gamma radiation comes from several surfaces, the exposure is increased. For example, if the radiation is coming from rock with a homogenous content of radioactive substances, the exposure is increased by about 30% if the radiation comes from a horizontal rock surface plus a nearby vertical rock surface. In a tunnel in which the radiation comes from all the walls, the exposure will be roughly 65% more than over a plane surface.

Soil	^{226}Ra, Bq/kg	^{232}Th, Bq/kg	^{40}K, Bq/kg	^{222}Rn, Bq/m^3
Gravel	10-90	2-80	300-1,100	10,000-150,000
Sand	<4-60	2-80	150-1,100	4,000-20,000
Eolian sand-silt	5-20	10-20	400-1,000	1,000-35,000
Silt	5-70	5-70	500-1,000	5,000-60,000
Clay	15-130	10-100	600-1,200	30,000-120,000
Till	10-170	15-100	500-1,200	20,000-100,000
Till with alum shale	180-2,500	30-50	600-1,200	50,000 - > 1 million

Table 4.2.2. Nordic soil types. Typical ranges of activity concentrations of radium-226, thorium-232 and potassium-40 in soil (Eriksson and Fredriksson 1981, Ennow and Magnusson 1982, Minell 1983, 1990, Evans and Eriksson 1983, Egnell-Jensen et al. 1984, Korsbech 1985, SGAB 1988, Åkerblom et al. 1988) and radon-222 in soil air at a depth of one meter in the soil (Åkerblom

Table 4.2.3 shows the exposure due to gamma radiation in air about one meter above the ground surface for normal conditions out-of-doors. Higher levels of gamma radiation than those shown in the Table occur over bedrock which contains higher than normal contents of uranium and/or thorium or over moraine formed from such rocks. In these cases it is a question of areas with acid plutonic rocks, e.g. granites, syenites, aplites, pegmatites and gneiss, acid volcanic rocks, e.g. porphyry, carbonatites or alum shale. Extensive areas with 0.2–0.3 µSv/h over about one or even many square kilometers occur in regions of granites with enhanced concentrations of uranium and thorium, for example in areas with Bohus-granite in the County of Bohuslän in Sweden and Östfold in Norway. Areas with enhanced gamma radiation due to carbonatites occur in the Fen-area in Norway, in Sweden and in Finland. The gamma radiation levels are 0.15–1 µSv/h in areas where the alum shale bedrock is exposed or where the alum shale forms a major part of the local soil cover. Where pegmatites rich in uranium and thorium occur, the gamma radiation is often 0.25–2 µSv/h. These areas can exceed 1,000 m^2.

Where there are mineralizations of uranium and thorium the

Table 4.2.3. Gamma radiation outdoors in the Nordic countries (ambient dose equivalent rate) (Arvela et al. 1995, Aakrog et al.1997, SGU 1998a, Stranden 1977, Stranden and Strand 1986, Strand 1999, Ennow and Magnusson 1982). (The exposure to cosmic radiation is included.)

Source	Normal values, [1)] µSv/h[1]				
	Sweden	Norway	Finland	Denmark	Iceland
Average exposure from land, including wetlands	0.08	0.08	0.07	0.08	0.03
Normal exposure range in areas of dry land	0.04-0.2	0.03-0.2	0.03-0.3	0.06	0.02-0.1
Areas of granites and carbonatites with enhanced U and Th.	0.2-0.4	0.2-0.7			

1) Locally, the gamma radiation can be considerably higher than the values shown in the normal values row. Maximum values and the size of the areas can be as high as: for granites 0.6 µSv/h and for carbonatites 0.5-2 µSv/h, and as large as some thousand square meters, for alum shale outcrops 2 µSv/h and several hectares, for pegmatites 2-10 µSv/h and from a few square metres to some hundreds of square metres, for uranium and thorium mineralizations 30-100 µSv/h and from a few square metres to some hundreds of square metres.

local gamma radiation close to the mineralization can be 2–30 µSv/h, in a few cases up to 100 µSv/h. The affected areas can exceed 1,000 m^2. However, they are usually much smaller, <10–100 m^2. Since there are no other means of knowing the local situation than to measure the gamma radiation at the spot, and this is not usually done, it happens that houses are built on sites where the exposure to gamma radiation is high.

4.3. Radon in soil air

In the air in the pores of soil, the normal radon content is 4,000–50,000 Bq/m^3 at a depth of one metre (Table 4.2.2). Where there are elevated radium contents, there are higher radon concentrations in the soil air (Åkerblom et al. 1988). Concentrations of 100,000–200,000 Bq/m^3 are common in moraines and gravel within areas with uranium-rich granite. In areas where the soil contains many fragments of alum shale or material from uranium occurrences, the radon concentration can be considerably greater than 1,000,000 Bq/m^3.

It is particularly common to find high radon concentrations in buildings in areas with alum shale and uranium-rich granites and in soils that have especially high permeability, for example gravel and coarse sand. From such soils, radon-containing soil air can easily be transported through the soil and then further into parts of buildings which are in contact with the ground.

4.4. Radon in outdoor air

Normal radon concentrations in outdoor air are 2–15 Bq/m^3, although in depressions and valleys, when there is inversion, local values of about 100 Bq/m^3 can occur.

4.5. Radon in buildings

Sources of radon in indoor air are the ground, the building materials and, in households, used groundwater. For parts of buildings in contact with the ground, radon from the ground is the dominant source of radon. In Sweden, the radon emanating from building materials is a major problem. There are about 300,000 dwellings with walls made of lightweight concrete based on alum shale.

When water-containing radon is used in a household, more than 50% of the radon reaches the indoor air. The radon emission from the water contributes to the radon concentration of the air but it is seldom the cause of high indoor concentrations.

Measurements in Swedish dwellings (Mjönes 1996) show that the gas radon-220 (thoron) is not an indoor problem in dwellings. The thoron concentrations are consistently low, mainly due to the fact that the thoron has time to decay before it reaches the building (the half-life of thoron is 55 seconds). On the other hand, there can be high concentrations of thoron in mines and underground rooms built in thorium-rich bedrock since the thorium then passes straight from the rock surface to the air. In houses built on such bedrock the thoron concentrations can be quite high (Stranden 1984).

Transport of radon from the ground to a building occurs actively together with soil air which is sucked into the building, or passively via diffusion from the ground surface. The active transport is completely dominant. Radon emanates from the building materials in the walls by diffusion directly into the indoor air.

National surveys of the radon concentration in randomly chosen dwellings have been made in all the Nordic countries except Iceland. The results are given in Table 4.5.1. This Table also shows the estimated number of dwellings that have indoor radon concentrations of more than 200 Bq/m^3 and 400 Bq/m^3, and the maximum annual average value ever measured in the living area of a dwelling. The values shown are not strictly comparable owing to different methods in selecting dwellings to be measured, different durations of the measurements and measurements made at different times of the year.

Table 4.5.1. Radon concentrations (annual average) in Nordic dwellings. The average results were obtained in national surveys of radon in randomly selected buildings. The maximum values represent the highest annual average radon concentration measured in the living area of a dwelling. The data given refer to the housing situation in 1998 as calculated from national surveys.

Numbers of dwellings within the country 1998	Number and percentage of measured dwellings in the national surveys		Arithmetic average, Bq/m³
Finland [1]			
All dwellings 2.4 M	3,074	0.14%	123
Apartments 1.1 M	903	0.09%	82
Single-family homes 1.3 M	2,171	0.18%	145
Sweden [2]			
All dwellings 4.0 M	1,360	0.034%	108
Apartments 2.1 M	646	0.031%	75
Single-family homes 1.9 M	714	0.038%	141
Denmark [3]			
All dwellings 2.16 M	496	0.02%	47
Apartments 0.93 M	148	0.02%	19
Single-family homes 1.23 M	348	0.03%	68
Norway [4]			
All dwellings 1.85 M	7,525	0.41%	75
Apartments 0.2 M	944	0.38%	41
Single-family homes 1.65 M	6,581	0.41%	80
Iceland [5]			
All dwellings 0.11 M	18		
Apartments 0.07 M			
Single-family homes 0.04 M			

[1] The estimated number of dwellings given in columns 5 and 6 refers to the conditions in Finland in 1998 based on the percentage found in the 1990-1991 national survey (Arvela et al. 1993, Voutilainen et al. 1997).

[2] The estimated number of dwellings given in columns 5 and 6 refers to the conditions in Sweden in 1998 based on the percentage found in the 1991-1992 national survey (Swedjemark et al. 1993).

[3] The estimated number of dwellings given in columns 5 and 6 refers to the conditions in Denmark in 1998 based on the percentage found in the 1985 national survey (Ulbak et al. 1988).

[4] The estimated number of dwellings given in columns 5 and 6 refers to the conditions in 1996 based on the percentage found in the 1987-1989 national survey (Strand et al. 1992, Strand et al. 2000). In this

Geometric average, Bq/m^3	Estimated number and percentage with 200 - 400 Bq/m^3		Estimated number and percentage with > 400 Bq/m^3		Maximum value ever measured, Bq/m^3
84	159,000	9%	66,000	3.6%	
63	9,000	1%	7,000	0.8%	6,600
98	150,000	13%	59,000	5.0%	33,000
56	260,000	6.5%	140,000	3.3%	
40	100,000	4.8%	90,000	2.4%	
78	160,000	8.4%	50,000	4.7%	84,000
37	40,000	2%	4,000	<0.2%	
18	0	0%	0	0%	110
52	40,000	3%	5,000	<0.4%	1,200
45	85,000	4.5%	45,000	2.5%	
30	3,500	1.4%	1,500	0.6%	4,000
50	81,500	5.1%	43,500	2.7%	65,000
					26

survey only houses built before 1980 were included. The figures for single-family homes have been corrected to the 1996 levels based on follow-up measurements in larger samples of randomly selected single-family homes in the period between 1991 and 1996. Recent, and not yet published, results show that the average level in the 1998 housing stock is significantly higher than those shown in the table for single-family homes (close to 100 Bq/m^3). Most homes in Norway with elevated levels of radon were built after 1980 (in fact 1/4 of the housing stock). The data for single-family homes includes all types of dwellings (also detached homes, vertically and horizontally separated two-family homes, etc.) except flats in blocks 1996.

5) The survey in Iceland was made in 1982. (Ennow and Magnusson 1982).

In Finland, the dwellings were checked using two successive half-year-long measurements. The detector was placed in a room on the ground floor. In Norway, one measurement was made in each dwelling. The detector was placed in a bedroom. The measuring time was 6 months; measurements have been made in all seasons of the year and the results have been recalculated as annual means. In Denmark, two measurements were made in each dwelling, in the living room and in a bedroom. The measurement time was 6 months; 50% of the measurements were made during the winter half and 50% during the summer half of the year. In Sweden, two detectors were used in each measured dwelling. The measurements were made during a three-month in the winter half of the year, and the values obtained were given as annual values without recalculation.

Radon is not only a problem in dwellings. In many buildings used for schools, day-care centres, offices, workshops etc. the radon concentrations are high. Investigations on radon concentrations in workplaces have been made in Finland, Sweden, Norway and Denmark. The results show that especially schools and daycare centres often have radon concentrations that exceed the national action levels. In Norway, for example, where radon measurements have been performed in 3,660 day-care centres the arithmetic mean radon concentration is 88 Bq/m^3, the geometric mean 45 Bq/m^3 and the maximum 2,800 Bq/m^3 (Strand et al. 2000). In the Appendix Table 4, results are given from measurements in workplaces in Finland.

4.6. Natural radioactivity in drinking water

In water from surface water sources the concentrations of natural radioactive substances are always low. As a rule, water from earth aquifers and rock aquifers in sedimentary rocks (such as sandstone) has relatively low concentrations. On the other hand, elevated and high concentrations often occur in the water in rock aquifers in crystalline basement rocks, particularly in rocks with high contents of uranium. In granitic regions the groundwater in the rock generally has a higher radon concentration than in regions with other types of bed-rock.

Most of the water consumers in the Nordic countries use water supplied by communal water services. In Sweden, Finland and Norway, most water consumers use water from surface water sources. In Denmark and Iceland the consumer water originates mainly from ground waters in sedimentary rocks in Denmark and volcanic rocks in Iceland. Water, which is delivered from waterworks, is often treated by aeration and it will have passed through various types of filtration to remove iron, manganese and calcium. Depending on the aeration process used, most of the radon or at least part of it is removed, and radium and other nuclides to a large extent fasten in the filters. If the water is pumped directly from a borehole via a pressure-tank to tap points, there is no reduction in the radon concentration except for that due to the natural radioactive decay of the radon during the transit time in the water system. The radon concentration in that water has therefore in principle a concentration almost as high as in the groundwater in the bedrock or the earth-layer from which the water is taken. The concentrations of radium and radon daughters are affected, however, since they fasten in the piping and also in filters, if there are filters between the water source and the taps.

It is principally the nuclides in the uranium series, which are found in water. Uranium itself is relatively easily dissolved and mobile, while thorium is sparingly soluble and the concentrations in water are generally low. The substances which give the greatest radiation doses due to the intake of water are radon and the nuclides which follow radon in the decay chain. Radium is not easily soluble and its activity concentration in water is generally low, 0.001–0.02 Bq/l, even if higher values do occur. Maximum activity concentrations of 10 Bq/l have been found. The activity concentrations of uranium-238 and uranium-234 in groundwater are usually 0.002–0.1 Bq/l, but they can be relatively high in areas with rocks rich in uranium and maximum activity concentrations exceeding 100 Bq/l occur. However, uranium has a low specific activity and as a rule it does not represent a radiation protection problem. Table 4.6.1 shows the concentrations of radon and radium-226 for various types of untreated water in the Nordic countries. The population-weighted average radon concentration in water from public waterworks for the five Nordic countries are given in Table 4.6.2.

In Sweden, measurements have been made on the radon concentrations in 1,853 randomly chosen wells. Of these, 577 were dug wells taking their water from soil aquifers and 1,276 were wells drilled in rock. The arithmetic mean concentration for the dug wells was 43 Bq/l and the median value was 19 Bq/l. For the drilled wells, the arithmetic mean was 203 Bq/l and the median value 86 Bq/l (SGU 1998b). The radon concentration exceeded 100 Bq/l in 47 %, 500 Bq/l in 11 % and 1,000 Bq/l in 4 % of the wells. In Norway, results have been collected from the analysis of water from 3,500 drilled wells. The radon concentration exceeded 100 Bq/l in 46 %, 500 Bq/l in 15 % and 1,000 Bq/l in 9 % of the wells (Strand et al. 1998).

In Finland, radon-222, uranium-238, uranium-234, radium-226, lead-210 and polonium-210 concentrations have been

Table 4.6.1. Radon-222 and radium-226 in Nordic groundwaters. Normal and maximum activity concentrations. (Aastrup 1981, Ennow and Magnusson 1982, SIS 1987, Kulich et al. 1988, Åkerblom et al. 1988, Salonen 1994, Strand et al. 1998, SGU 1998b, Lind et al. 2000).

Type of water	^{222}Rn, Bq/l	^{226}Ra, Bq/l
Lake and sea water	< 1	0.005 - 0.007
Wells dug in soil:		
Normal in Sweden, Norway, Finland and Bornholm	10 - 300, max. 3,500	0.001 - 0.09, max. 0.3
In granitic areas	40 - 400	
Normal in Denmark	< 10	< 0.01
Wells drilled in sedimentary rocks:		
Eocambrian –Tertiary in Sweden, Norway and Denmark	≤ 1 - 50	
Wells drilled in volcanic rocks and sediments in Iceland:	< 5	
Geothermal areas	1-10	
Wells drilled in crystalline Precambrian bedrock:		
Normal bedrock	50 - 500	0.01 - 0.25
Uranium-rich granites	300 - 4,000, max. Swe. 89,000, Fin. 77,500, Nor. 32,000, Den. (Bornholm) 1,100	0.05 - 0.8, max. 7.5
Uranium-rich pegmatites	max. 15,000 - 30,000	max. 0.35 - 2.5
Water from exploration drillholes in uranium ores:		
Lilljuthatten, Stenfjällen	2,000 - 100,000	max. 6
Pleutajokk, Arjeplog	18,000 - 55,000	0.1 - 0.17

measured in water from about 1,000 waterworks, about 6,000 private wells drilled in bedrock and from about 4,000 private wells dug in soil (Appendix Table 3). The measurement data has been combined with the population statistics (Mäkeläinen et al. 1999) to provide means to estimate the overall situation in the country. The population weighted mean radon concentration is estimated as being 27 Bq/l for waterworks, 45 Bq/l for wells dug in soil and 540 Bq/l for wells drilled in bedrock. The percentages of consumers using water exceeding 100 Bq/l are 4%, 12% and 60% for water works, wells dug in soil and drilled wells respectively. The radon concentration in water from drilled wells exceeds 100 Bq/l in 60%, 300 Bq/l in 30%, 1000 Bq/l in 10% and 3000 Bq/l in 3% of the wells.

In Sweden, about 800,000 persons are dependent on drinking water from drilled wells, in Finland and Norway the corresponding numbers are about 200,000.

Country	Persons that use public water	^{222}Rn. Population weighted average, Bq/l	^{226}Ra. Population weighted average, Bq/l
Finland	4,000,000	27	0.003
Sweden	7,670,000	10	0.005
Denmark	5,000,000	< 10	< 0.01
Norway	3,500,000 [2)]	< 10	< 0.01
Iceland	265,000		

1) The data are from 1997. The population in Sweden in 1999 was 8.86 million.
2) This is an estimate.

Table 4.6.2 Consumption water supplied by public waterworks in the Nordic countries. Population weighted averages (Kulich et al. 1988, Salonen 1994, Strand 1999).

4.7. Natural radioactive elements in building materials

All wood-based building materials have low concentrations of natural radioactive substances. In stone-based building materials the concentrations depend on which products are included (Table 4.7.1). Sand, cement and lime have low concentrations, although cement can contain fly ash from the combustion of coal and it then has somewhat higher contents (outside the Nordic countries, fly ash with high concentrations of radium has been used). An aggregate in the building material consisting of crushed stone often has the greatest significance for the total radioactivity of the material. If radium-rich and thorium-rich granites are included as aggregates in concrete, the indoor gamma radiation from the walls and floors may be appreciably higher than the average outdoors. In many buildings in which the walls and floors are made of concrete containing aggregate of granite or basic gneiss with high contents of uranium, the indoor gamma radiation level is 0.2–0.3 µSv/h (Table 4.7.3). Such radiation levels also occur in Swedish buildings, which have walls of certain types of bricks made of glacial clays with enhanced uranium and thorium concentrations.

Even higher radiation levels occur in buildings where lightweight concrete based on alum shale ("blue concrete") has been used as the building material in the walls and joists. A normal gamma radiation level in dwellings with blue concrete is 0.3–0.5 µSv/h, but in about 25,000 dwellings in Sweden with blue concrete the radiation level exceeds 0.5 µSv/h, with a maximum gamma radiation level of 1.2 µSv/h. In Sweden, this blue concrete was used in the walls, floors or ceilings of about 300,000 dwellings. In Finland, Norway and Denmark there are a few buildings in which this blue concrete manufactured in Sweden was used. Higher levels of gamma radiation than 1.2 µSv/h occur in buildings built of blocks of slag from iron production in which uranium rich iron ore has been used. Up to 2 µSv/h has been found in Sweden.

Radon, which emanates from the materials in walls, floors and ceilings can give rise to increased radon concentrations indoors. The magnitude of the radon exhalation from various parts of the building depends on the radium concentration in the material and the materials' porosity, humidity and permeability and the wall thickness. Examples of materials with high contents of radium, and which therefore give rise to radon exhalation problems, are "blue concrete," gypsum board made of phospho-gypsum (a by-product from the production of phosphoric acid) and building elements and blocks made of slag. Table 4.7.2 shows Finnish and Swedish measured values for radon exhalation from untreated wall-surfaces.

Table 4.7.1. Nordic building materials and activity concentrations (Ulbak 1979, Ennow and Magnusson 1982, Mustonen 1984, Möre 1985).

Building material	^{226}Ra, Bq/kg	^{232}Th, Bq/kg	^{40}K, Bq/kg
Wood materials	0.3-0.5	0.2-1.5[1]	8-12
Natural building stones	0.5-400	1-350	20-1,800
Bricks made of clay	25-160	70-180	550-1,100
Bricks made of limestone and sand	6-25	4-30	20-440
Cement	10-190	<4-110	<20-380
Concrete [2]	5-160	3-390	80-1,200
Light-weight concrete made of limestone and sand	7-130	4-150	25-670
Light-weight concrete made of alum shale	650-2,600	20-80	450-1,110
Blocks of expanded clay	120-140	110-180	730-1,100
Gypsum board made of natural gypsum	2-11	<1-12	<3-25
Gypsum board made of phospho-gypsum [3]	590-630	<16-18	40-100

1) Radium-228

2) The maximum values refer to concrete with an aggregate of granite rich in uranium and thorium.

3) Gypsum boards made of phospho-gypsum have been used in Finland (they are no longer used), but not in Sweden, Norway or Denmark.

Table 4.7.2 Radon exhalation from untreated wall surfaces (Håkansson and Möre 1981, Petterson et al. 1982, Mustonen 1984).

Building material	^{226}Ra, Bq kg^{-1}	^{222}Rn exhalation exhalation, Bq m^{-2} h^{-1}	Note	Measurements performed at [1]
Concrete	60	13	One sample	SP
Concrete		7.5	One sample	SSI
Concrete	40-60	16-32	Eight samples	STUK
Bricks		0.4	One sample	SSI
Sand-based lightweight concrete	10-130	1-3	Two samples	SSI
By-product gypsum	320-482	5-42	Five samples	STUK
Alum-shale based lightweight concrete	1,180	50	One sample	SSI
Alum-shale based lightweight concrete	1,500	104	One sample	SP
Alum-shale based lightweight concrete	2,500	205	One sample	SP

[1] SP (Swedish National Testing Institute), SSI (Swedish Radiation Protection Institute), STUK (Radiation and Nuclear Safety Authority, Finland).

From time to time buildings are found with their foundations on occurrences of uranium and thorium, e.g. uranium-rich pegmatites or dykes of thorium-rich carbonatite. The gamma radiation level in such a building may be as high as 3 μSv/h or even more. Values for normal and maximum indoor levels of external gamma radiation in different types of buildings are given in Table 4.7.3.

When new buildings are to be built, it is possible to plan and build in such a manner that the radiation levels do not reach unacceptably high values. The radiation above the ground and around the building can be checked and it is possible to select building materials with acceptable concentrations of natural radioactive substances.

Source	Normal range, [1] µSv/h				
	Finland	Sweden	Denmark	Norway[1]	Iceland
Average exposure	0.07	0.13	0.10	0.09	0.03
In wooden houses (The indoor gamma radiation is from the surrounding ground)	0.02-0.10	0.04-0.15 average 0.07	0.08	0.08	
In houses made of bricks, concrete and stone materials	0.05-0.18	0.03-0.3 average 0.14	0.08-0.12 average 0.10	0.07-0.20 average 0.13	0.02-0.04
In houses of alum-shale based light-weight concrete. 300,000 dwellings are built of such material		0.3-0.5			

Table 4.7.3. External gamma radiation indoors in the Nordic countries (ambient dose equivalent rate), exposure from cosmic radiation is included. (Mjönes 1981, Mjönes 1986, Ulbak et al. 1988, Arvela et al. 1995, Stranden and Strand 1986.)

[1] Higher gamma dose rates exist in buildings built on soils and rocks that contain enhanced uranium and thorium concentrations, e.g. granites, pegmatites, carbonatites and alum shale or built of such rock types or slag. Maximum gamma dose rates measured indoors in dwellings due to gamma radiation from the ground are: In Sweden, about 2 µSv/h, due to use of slag blocks 2 µSv/h and due to building materials containing alum shale 1.2 µSv/h. In Norway, due to use of carbonatites in stonewalls 2.3 µSv/h and in Denmark, in brick buildings, 0.26 µSv/h.

5. Radon in indoor air – recommendations

5.1. Introduction

When high radon levels occur, the individual risk of lung cancer is sometimes considerably higher than other important risk factors in society and remedial measures are therefore highly justified. It is important to identify buildings (dwellings or workplaces) with radon concentrations exceeding the action levels adopted by the competent authorities and to take steps further to reduce the exposure. Exposure to radon poses not only an important individual health risk for people exposed to elevated levels of radon, but also an important collective risk for the whole population. Radon exposure in dwellings is an important collective risk compared to many other collective risks in society, and the national radon policy should also include general recommendations to reduce the average level and thereby the collective risk of radon exposure to the population.

In existing buildings, the exposures can only be reduced by some form of intervention (remedial measures). Usually, intervention (existing dwellings) is much more expensive than preventive measures (new dwellings). The general recommendation is that preventive measures should be introduced with the aim of avoiding levels of radon above the national average for different types of buildings (both dwellings and workplaces) and that the levels in the remediated buildings should be as low as reasonably achievable.

5.2 Radon in existing dwellings

5.2.1. Investigation and action levels

- **The recommended investigation level for radon in existing dwellings is 200 Bq/m^3.**

- **The recommended action level for radon in existing dwellings is 400 Bq/m^3.**

Remedial measures in dwellings should be considered when the annual mean radon gas concentration in the living area exceeds 200 Bq/m^3. In the range between 200 and 400 Bq/m^3 simple and low cost measures are recommended. At levels exceeding 400 Bq/m^3, remedial measures should be undertaken with the aim of bringing the radon level below 200 Bq/m^3. Remedial measures should be cost-effective and based on well-proven techniques.

5.2.2. Measurements

Indoor radon measurements should be based on reliable methods approved by national authorities. The integration time should be at least two months during the heating season, in order to average out short-term variations in the radon concentration.

Action levels refer to annual mean levels. Indoor radon concentrations are generally somewhat higher in the winter than in the summer, and appropriate correction factors to convert the results to annual mean levels could be applied.

5.2.3. Strategies to identify radon-prone areas

The only way to identify dwellings above the action level is by making radon measurements in indoor air. A well-defined strategy to identify areas in which dwellings above the action level are likely to exist should be established by the national authorities.

It is recommended that the classification of radon-prone areas is based on measurements in a representative sample of the building stock combined with the use of information on geology and building construction.

5.3 Radon in workplaces

- **The recommended action level for radon in aboveground workplaces during working hours is 400 Bq/m^3.**

- **An action level for radon in underground workplaces within the interval 400 – 1,500 Bq/m^3, expressed as the average activity concentration during working hours, is recommended.**

If it is not possible to reduce the radon level below the action level, the workplace should be treated in the same way as a practice. This would imply the applications of dose limits.

Remedial measures at aboveground workplaces should be considered when the annual mean radon concentration during working hours exceeds 400 Bq/m^3. Authorities may take into consideration the annual occupancy.

The relevant national authorities must decide if and where employers need to measure radon levels in workplaces. It is, however, likely that measurements are needed at most underground workplaces or at least in a large enough sample for a clear statistically significant picture to be obtained.

Aboveground workplaces include office buildings, factories, schools, day-care centres or nursery schools, etc. In schools and nursery schools the occupancy factor is about the same as in workplaces and should therefore in principle be treated in the same way. However, because of the large number of individuals per building (or room) and because the main occupants are children, it is recommended that schools and nursery schools are treated in same way as dwellings.

Underground workplaces where radon concentrations may require supervision include mines (except open-cast mines), tunnels, hydroelectric power stations, underground defence installations, subways, show caves and tourist mines, and underground water treatment works and stores.

5.4 Radon in new buildings

- **The recommended upper level for radon in new buildings is 200 Bq/m^3.**

New buildings include dwellings and aboveground workplaces and other buildings utilised more than temporarily. New buildings should be planned and constructed in such a way that the annual average radon concentration will be as low as reasonably achievable.

6. Natural radioactivity in drinking water – recommendations

6.1. Introduction

The naturally occurring radionuclides which may be present in drinking water are radon-222 and its short-lived daughters and uranium-238, uranium-234, radium-226, lead-210 and polonium-210. From the dose point of view the most important of these are radon-222, polonium-210 and lead-210. In cases in which the radon concentration of the water is high, several thousands of Bq/l, and the amount of radon has been decreased through aeration, short-lived radon daughters may also be a cause of high doses.

Most of the dose to the population from natural radioactivity in drinking water is due to radon through inhalation and ingestion. In most situations, the levels of other nuclides are so low that there is no need for remedial action. High radon concentrations indicate the potential presence of other nuclides in the uranium decay series in the water, although the correlation is not always unambiguous. Only when the radon concentration of water is high there is reason to suspect that the concentrations of other nuclides may also be high.

6.2. Radon in drinking water

- **The recommended exemption level for radon in drinking water is 100 Bq/l.**
- **The recommended upper level for radon in drinking water is 1,000 Bq/l.**

6.3. Long-lived radionuclides in drinking water

The most important long-lived naturally occurring radionuclides which may be present in drinking water are uranium-238, uranium-234, radium-226, lead-210 and polonium-210.

- **The recommended upper level, expressed as annual effective dose, for exposure to long-lived radionuclides in drinking water is 1 mSv.**

National authorities may also select an upper level below 1 mSv per year if they judge that it is desirable and will not lead to an unmanageable number of wells for which action is required.

6.4. Recommendations for measurements

Because it is important to identify high-risk areas, it is recommended that in each country a measurement strategy should be established, through surveys or by other means, to find the areas where analysis of radon, and possibly other naturally occurring radionuclides, in the drinking water should be carried out.

National authorities should also issue recommendations about the sampling and reliable measurement methods to be used. Special procedures should be adopted in the sampling to prevent radon escaping from the sample.

It is recommended that the water from a drilled well should be analysed for radon when a new well is taken into use in cases where the bedrock consists of igneous rocks.

7. Exposure from gamma radiation – recommendations

The dose to humans from gamma radiation from natural radioactive elements originates partly from the ground and partly from building materials. Ground where the gamma radiation is higher than average to such an extent that some precautions may be considered is found in some places in Sweden, Norway and Finland, mainly in connection with pegmatite rocks, alum shale and mineralizations of uranium and thorium. No such localities are known from Denmark or Iceland.

In some building materials the activity concentration can be so high that the exposure to indoor gamma radiation is unnecessarily high. Examples of such building materials are the Swedish lightweight concrete made of alum shale and some products containing slag, certain types of coal ash or phospho-gypsum.

7.1. Exposure to gamma radiation in buildings and at often used places outdoors

7.1.1. Existing buildings

- **The recommended upper level for exposure to external gamma radiation in existing buildings, expressed as ambient dose equivalent rate, is 1 μSv per hour.**

7.1.2. New buildings

- **The recommended upper level for exposure to external gamma radiation in new buildings, expressed as ambient dose equivalent rate, is 0.5 μSv per hour.**

7.1.3. Often used places outdoors

- **The recommended investigation level for exposure to gamma radiation at often used places outdoors, e.g. playgrounds, expressed as ambient dose equivalent rate, is 1 μSv per hour.**

7.2. Building materials

To ensure that the building materials will not give rise to enhanced radon and gamma radiation levels indoors in new constructions, the activity concentrations of naturally occurring radionuclides should be controlled. Building materials that can have significance for radon and gamma radiation levels indoors are primarily those, which are used for construction of walls and floor structures. Materials that are used in small volumes or only as facade materials normally have little impact on radon and gamma radiation levels indoors.

7.2.1. Building materials as a source of indoor radon

- **The recommended exemption level for the activity concentration of radium-226 in building materials for new constructions as a source of indoor radon is 100 Bq per kg.**

■ **The recommended upper level for the activity concentration of radium-226 in building materials for new constructions as a source of indoor radon is 200 Bq per kg.**

If the upper level is exceeded for a particular material, an assessment of the contribution of the material to the indoor radon concentration should be made. The assessment should be based on a realistic view of the use of the material and it should take into consideration the amount of the material which is used and in what parts of the building it is used.

When a building material with a radium concentration at the upper level is used in all materials surrounding a room, a radon gas concentration of up to 200 Bq/m^3 could be expected from this source for various types of houses, if the ventilation rate is 0.5 air changes per hour.

When the radium-226 concentration is below 100 Bq/kg (the exemption level) in the materials it is unlikely that the radon exhalation from the building materials will cause indoor radon concentrations exceeding 200 Bq/m^3.

7.2.2. Building materials as a source of gamma radiation in new constructions

■ **The recommended exemption level for the activity concentrations in building materials as a source for gamma radiation in new constructions should be determined by the inequality**

$$m_\gamma < 1$$

■ **The recommended upper level for the activity concentration in building materials as a source for gamma radiation in new constructions should be determined by the inequality**

$$m_\gamma < 2$$

where $m_\gamma = C_K/3000 + C_{Ra}/300 + C_{Th}/200$ *and* C_K is the concentration of potassium-40, C_{Ra} the concentration of radium-226 and C_{Th} the concentration of thorium-232, all in Bq/kg.

If the recommended levels are exceeded for a particular material, an assessment of the contribution of the material to the indoor gamma radiation level should be made. The assessment should be based on a realistic view of the use of the material and take into consideration the amount of the material which is used and in what parts of the building it is used.

At the exemption level, the average annual effective dose is estimated to be 1 mSv when all the surrounding surfaces are of the same material, at the upper level 2 mSv.

The European Commission has published a guidance paper on natural radioactivity in building materials (EC 1999). In the guidance paper it is recommended, for the excess gamma radiation originating from building materials, the use of national dose criteria for control in the range from 0.3 to 1.0 mSv per year and the use of a general exemption level of 0.3 mSv per year. For the Nordic countries, however, exemption levels of 1 mSv per year for national building materials can in some cases be justified.

8. References

Aakrog, A.: Risö Report No. 953 1997.

Aastrup, M.: “Naturligt förekommande uran-, radium- och radonaktiviteter i grundvatten”. SKBF, Teknisk rapport 81-08. 1981.

Åkerblom, G., Pettersson, B., Rosén, B.: “Markradon. Handbok för undersökning av markradonförhållanden”. In the Series: “Radon i bostäder”. The Swedish Council for Building Research. Report R85: 1988, revised 1990. Stockholm. 1988.

Åkerblom, G., Mellander, H.: “Geology and Radon”. In ”Radon Measurements by Etched Track Detectors”. (Editors: Durrani, S. A., Ili´c, R.). Word Scientific. 1997.

Åkerblom, G.: “Concentrations of Radium-226, Thorium-232 and Potassium-40 in different types of rocks. Results compiled from different publications and from gamma ray spectrometric field measurements made during uranium exploration and geological surveys in the Nordic countries”. Personal communication. 1999.

Annanmäki, M., Markkanen, M., Oksanen, E.: “Monitoring of radon in workplaces – Finnish approach”. Annalen van de Belgische Vereniging voor Stralings-bescherming, Vol. 21, No 1, pp. 75-81. 1996

Arvela, H., Mäkeläinen, I., Castrén, O.: “Otantatutkimus asuntojen radonista Suomessa (Residential radon survey in Finland). Säteilyturvakeskus. Report STUK-A108. 1993.

Arvela, H., Hyvönen, H., Lemmelä H., Castrén O.: "Indoor and outdoor gamma radiation in Finland". Radiation Protection Dosimetry, Vol. 59, No. 1, pp. 25–32. Nuclear Technology Publishing. 1995.

Egnell-Jenssen, M., Korsbech, U., Engström Madsen, F. "Th and K in Upper Cretaceous and Tertiary sediments in Denmark". Bulletin of the Geological Society of Denmark. Vol. 32, pp. 107–120. 1984.

Ennow, K. R., Magnusson, S. M.: "Natural radiation in Iceland and the Faroe Islands". National Institute of Radiation Hygiene, Copenhagen. SIS Report Nov. 1982.

Eriksson, Å., Fredriksson, L.: "Naturlig radioaktivtet i mark och grödor". Swedish University of Agricultural Sciences, Department of Radiobiology, Uppsala. Report SLU-IRB-52. 1981.

EC, 1990: "Commission Recommendation of 21 February 1990 on the protection of the public against indoor exposure to radon". European Communities. 90/143/ Euratom. 1990.

EC, 1996: "Council Directive 96/29/EURATOM of 13 May 1996 laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation. Legislation". Official Journal of the European Communities. L159, Vol.39. 1996.

EC, 1997: "Recommendations for the implementation of Title VII of the European Basic Safety Standards Directive (BSS) concerning significant increase in exposure due to natural radiation sources". Radiation Protection 88.

Directorate-General Environment, Nuclear Safety and Civil Protection. Office for Official Publications of the European Commission. Radiation Protection Series. European Commission. 1997.

EC, 1998: “Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption”. Official Journal of European Communities. L 330/32-54. 5.12.98. 1998.

EC, 1999: “Radiological protection principles concerning the natural radioactivity of building materials”. Radiation Protection 112. Directorate-General Environment, Nuclear Safety and Civil Protection. Office for Official Publications of the European Commission. Radiation Protection Series. European Commission. 1999.

Evans, S., Eriksson, Å.: “Uranium, thorium and radium in soils and crops – Calculations of transfer factors”. Swedish Nuclear Fuel Supply Co/Divison KBS. SKBF/KBS Technical report 83-73. 1983.

Håkansson, B., Möre, H.: “Radonavgång från byggnadsmaterial. Mätmetod för bestämning av radonexhalation från byggnadsmaterial”. Statens strålskyddsinstitut, Rapport a 81-19. 1981.

IAEA: “The use of gamma ray data to define the natural radiation environment”. International Atomic Energy Agency, IAEA-TECDOC-566, Vienna. 1990.

ICRP 23: “Report of the Task Group on Reference Man”. ICRP Publication 23. Pergamon Press. 1975.

ICRP 38: “Radionuclide transformations. Energy and intensity of emissions”. Annals of the ICRP. ICRP publication 38. Vol. 11-13. Pergamon Press. 1983.

ICRP 60: “1990 Recommendations of the International Commission on Radiological Protection”. ICRP Publication 60. Annals of the ICRP 21(13). 1991.

ICRP 65: “Protection against Radon-222 at Home and at Work. A Report of the International Commission on Radiological Protection”. ICRP Publication 65. Pergamon Press. 1993.

ICRU: “Conversion Coefficients for use in Radiological Protection against External Radiation”. International Commission on Radiological Units and Measurements, Bethesda, MD. ICRU Report 57. 1998.

Korsbech, U.: “Radon exhalation from samples of Danish soils, subsoils and sedimentary rocks”. The Technical University of Denmark, Department of Electrophysics. Report, January 1985.

Kulich, J. Möre, H., Swedejemark, G. A.: “Radon och radium i hushållsvatten”. Statens strålskyddsinstitut, SSI-rapport 88-11. 1988.

Lind, B., Strand, T., Frengstad, B.: “Radon i hushållsvann fra borebrönner i Norge”. Statens strålevern. Report (in press). 2000.

Mäkeläinen, I., Salonen, L., Huikuri, P., Arvela H.: “Dose from drinking water in Finland”. In: Nordic Society of Radiation Protection, proceedings of the 12th ordinary meeting Skagern, Denmark. 23–27. 8.1999. (Editors: Sörgaard-Hansen J. and Damkjear A.). IRPA/NSFS. 1999.

Markkanen, M. “Radiation Dose Assessments for Materials with Elevated Natural Radioactivity”. Säteilyturvakeskus. Report STUK-B-STO 32. 1995.

Markkanen, M.: Personal Communications. 1999.

Minell, H.: “Gammastrålning och halter av K, U och Th i svenska jordarter”. Geological Survey of Sweden. Report IRAP 83051. 1983.

Minell, H. “Natural radioactivity from different ground types”. In: “Quaternary Economic Geology in the Nordic Countries”. (Editors: Kauranne, L. K. and Königsson, L. K.). Uppsala. Vol. 29, pp. 73–78. 1990.

Mjönes, L.: “Gamma radiation in Swedish dwellings”. Rad. Prot. Dosim. 15(2): pp. 131–140. 1986.

Mjönes, L.: “Gammastrålning i bostäder”. Statens strålskyddsinstitut, Arbetsdokument a 81-18. 1981.

Mjönes, L., Falk, R., Mellander, H., Nyblom, L., Nilsson, I.: “^{220}Rn and its progeny in buildings in Sweden”. In the Natural Radiation Environment VI (Editors. Hopke, P. H. et al.). Proceedings of the Sixth International Symposium on the Natural Radiation Environment (NRE-VI), Montreal, Quebec, Canada, 5–9 June 1995. Environment International. Vol. 22, Supplement 1, ISSN 0160-4120, pp. 1125–1133. 1996.

Mustonen, R.: “Natural radiation in and radon exhalation from Finnish building materials”. Health Physics, Vol. 46, No. 6, pp. 1195–1203. 1984.

Möre, H.: “Radioaktiva ämnen i byggmaterial”. Statens strålskyddsinstitut, SSI-rapport 85-08. 1985.

Nordic, 1986: “Naturally occurring radiation in the Nordic Countries – Recommendations”. The Radiation Protection Institutes in Denmark, Finland, Iceland, Norway and Sweden. The Flag-book series. Reykjavik. 1986.

NRC, 1999: “Risk Assessment of Radon in Drinking Water”. Committee on Risk Assessment of Exposure to Radon in Drinking Water. Board on Radiation Effects Research, Commission on Life Sciences. National Research Council, National Academy Press. Washington DC. 1999.

Petterson, H., Hildingsson, O., Samuelsson, Ch., Hedvall, R.: “Radonexhalation från byggnadsmaterial”. Swedish National Testing Institute. Teknisk rapport SP-RAPP 1982:32. 1982.

Risö: “Environmental radioactivity in Denmark in 1984”. Risö Report R-527. Risö. 1985.

Salonen, L.: “^{238}U series radionuclides as a source of increased radioactivity in groundwater originating from Finnish bedrock. Future groundwater resources at risk”. Proceedings of the Helsinki Conference. June 1994. IAHS Publ. No.22, 1994, pp. 71–83. 1994.

Salonen, L.: “Luonnon radioaktiiviset aineet pohjavesiongelmana Suomessa.” Vesitalous 4, pp. 13–18, 1995.

SGAB: “Compilation of results from gamma-ray spectrometric measurements in dug pits in soil”. Swedish Geological Co. 1988.

SGU: “Natural Ground Gamma Radiation Map based on gamma-ray spectrometric airborne measurements over the Swedish territory 1968–98”. Swedish Geological Survey. 1998 a.

SGU: Information from the Archive on Wells. Swedish Geological Survey. 1998 b.

SIS: “Radioaktive stoffer i drickevand”. Statens Institut for Strålehygiene. 1987.

SSI: “Radon – Risk – Stråldos; Bostäder och arbetsplatser”. Statens strålskyddsinstitut, SSI i 94–06. 1994.

Strand, T., Green, B. R. M., Lomas, P. R.: “Radon in Norwegian dwellings”. Radiation Protection Dosimetry, 45 (1/4), pp. 503–508. 1992.

Strand, T., Lind, B., Thommesen, G.: “Naturlig radio-aktivitet i husholdningsvann fra borebrönner i Norge”. Norsk Vetrinärtidskrift, 110, (10), pp. 662–665. 1998.

Strand, T.: Personal communication. Statens stråleveren. 1999.

Strand, T., Heiberg, A., Thommesen, G.: “Radon i norske boliger 1999”. Statens strålevern. Report (in press). 2000.

Strand, T., Birovljev, A., Heiberg, A.: “Radon i norske barnehager”. Statens strålevern. Report to be published. 2000.

Stranden, E., Strand, T.: “Natural gamma radiation in a Norwegian area rich in thorium”. Radiation Protection Dosimetry, 16 (4), pp. 325–328. 1986.

Stranden, E.: “Thoron (^{220}Rn) daughter to radon (^{222}Rn) daughter ratios in thorium-rich areas”. Health Phys. 47(5), pp. 784–785. 1984.

Stranden, E.: “Population doses from environmental gamma radiation in Norway”. Health Phys. 33, pp. 319–323. 1977

Swedjemark, G. A., Lindén, A.: “Radon removal: Its effect on short-lived radon progeny and implications for effective dose”. Radiation Protection Dosimetry, Vol. 80, No. 4, pp. 405–409. 1998.

Swedjemark, G. A., Mellander, H., Mjönes, L.: “Radon. In: The indoor climate in Swedish residential buildings” (in Swedish with English abstract). (Editors: Norlén, U. and Andersson, K.). Swedish Building Research Institute, Report TN:30. 1993.

Ulbak, K.: “Natural radioactivity in building materials in Denmark”. Proceedings of Seminar on the Radiological Burden of Man from Natural Radioactivity in the Countries of the European Communities. Commission of the European Communities. 1979.

Ulbak, K., Sternum, B., Sörensen, A., Majborn, B., Bötter-Jensen, L., Nielsen, S. P.: “Results from the Danish Indoor Radiation Survey”. Radiation Protection Dosimetry, Vol. 24, No. 1/4, pp. 401–405. 1988.

UNSCEAR, 1982: “United Nations Scientific Committee on the effects of Atomic Radiation. Report to the General Assembly, with annexes”. United Nations, New York, 1982.

UNSCEAR, 1993: "United Nations Scientific Committee on the effects of Atomic Radiation. Report to the General Assembly, with scientific annexes". United Nations 54. ISBN 92-1-1-142200-0. 1993.

Voutilainen, A., Mäkeläinen, I., Reisbacka, H., Castrén, O.: "Asuntojen radonpitoisuus Suomessa". Säteilyturvakeskus. STUK Report A-146, Helsinki. 1997.

9. Appendix

Information of general interest from results of measurements and analyses of natural radionuclides in Nordic soils, water, building materials and indoor radon concentrations is given in this Appendix. Common for these data is that they have not been obtained as results of measurements and analyses of randomly chosen samples or objects, but they nevertheless provide valuable information on the natural radioactivity.

The decay series for uranium-238, uranium-235 and thorium-232 and the decay scheme of potassium-40 are also included in the Appendix.

Table 1.
Swedish soil: Typical values of activity concentrations of radium-226, thorium-232 and potassium-40 in soil samples representative for Sweden. Analyses made by in situ gamma ray spectrometric measurements in dug pits (Minell 1983, SGAB 1988).

Soil	Number of samples	^{40}K, Bq/kg		^{226}Ra, Bq/kg		^{232}Th, Bq/kg	
		Mean	Range	Mean	Range	Mean	Range
Gravel	118	900	512-1,160	43	12-86	44	28-68
Sand	49	802	628-1,163	26	10-57	30	2-75
Silt	35	841	465-961	31	15-66	31	5-64
Clay	78	1042	627-1,178	64	30-123	77	30-100
Till	125	775	558-1,147	42	12-165	42	14-94
Till with alum shale	10	697	589-1,174	595	381-984	41	32-48

Table 2.
Typical activity concentrations of radium-226, thorium-232 and potassium-40 in soil in southern Finland (Markkanen 1999).

Soil type	Activity concentration, Bq/kg		
	^{226}Ra	^{232}Th	^{40}K
Gravel	20-60	20-60	500-1,000
Sand	20-60	20-60	500-1,000
Silt	40-90	30-60	600-1,100
Clay	50-100	40-80	700-1,100
Till	30-100	30-80	600-1,100

Table 3.
Average concentrations of naturally occurring radionuclides in drinking water supplied by waterworks and private wells in Finland. Results from analyses of water samples from more than 1,000 waterworks, about 6,000 wells drilled in bedrock and 4,000 dug wells (Mäkeläinen et al. 1999)

Nuclide	Waterworks, Bq/l	Wells dug in soil, Bq/l		Wells drilled in bedrock, Bq/l		Weighted mean, Bq/l
	Average	Average	Max.	Average	Max.	
^{222}Rn	27	45	3,600	540	77,000	46
^{238}U	0.015	0.02	1.1	0.25	151	0.025
^{234}U	0.02	0.02	1.2	0.4	289	0.035
^{226}Ra	0.003	0.01	2	0.07	49	0.006
^{210}Pb	0.004	0.04	1.4	0.1	21	0.011
^{210}Po	0.003	0.01	1.3	0.06	16	0.006

Table 4.
Radon in workplaces in Finland. Measurement data for different types of workplaces. The table shows the arithmetic mean (AM), the number of measurements (N) and the percentages of the results exceeding 300 Bq/m^3. Category I includes municipalities where more than 25% of the radon concentrations measured in dwellings exceeded 400 Bq/m^3. In municipalities belonging to category II the corresponding percentage varied from 10 to 25%. (Annanmäki et al. 1996).

	Arithmetic mean, Bq/m^3	Number of measurements, N	Percentage exceeding, 300 Bq/m^3
Municipalities in category I			
Local government workplaces	505	426	25
Schools and nurseries	531	271	34
Other	460	155	37
Businesses	255	3,050	19
Municipalities in category II			
Local government workplaces	290	995	18
Schools and day nurseries	294	595	19
Other	284	400	17
Businesses	171	883	12

Table 5.
Uranium-238 series (ICRP 1983)

Nuclide	Type of decay	Half-life	Average emitted energy per transformation		
			Alpha energy, MeV	Beta energy, MeV	Gamma energy, MeV
Uranium-238 ^{238}U	α	4.479 10^{9}y	4.26	0.010	0.001
⇓					
Thorium-234 ^{234}Th	β	24.1 d	–	0.059	0.009
⇓					
* Protactinium-234m ^{234m}Pa (99.84%) +	β	1.17 m	–	0.820	0.013
* Protactinium-234 ^{234}Pa (0.16%)	β	6.7 h			
⇓					
Uranium-234 ^{234}U	α	2.45 10^{5}y	4.84	0.013	0.002
⇓					
Thorium-230 ^{230}Th	α	7.54 10^{4}y	4.74	–	0.002
⇓					
Radium-226 ^{226}Ra	α	1600 y	4.86	–	0.007
⇓					
Radon-222 ^{222}Rn	α	3.824 d	5.59	–	–
⇓					
Polonium-218 ^{218}Po	α (99%) + β (0.02%)	3.05 m	6.11	–	–
⇓					
* Astatine-218 ^{218}At 0.02%	α	1.6 s	6.82	0.04	–
* Lead-214 ^{214}Pb 99.98 %	β	26.8 m	–	0.291	0.284
⇓					
Bismuth-214 ^{214}Bi	β (99%) + α (0.04) %	19.9 m	–	0.648	1.46
⇓					
* Polonium-214 ^{214}Po 99.98%	α	1.64 10^{-4}	7.83	–	–
*Tallium-210 ^{210}Tl 0.02%	β	1.3 m	–		
⇓					
Lead-210 ^{210}Pb	β	22.3 y			0.047
⇓					
Bismuth-210 ^{210}Bi	β	5.01 d	–	0.389	
⇓					
Polonium-210 ^{210}Po	α	138.4 d	5.40	–	–
⇓					
Lead-206 ^{206}Pb		Stable			

* Branched decay

Table 6.
Uranium-235 series (ICRP 1983)

Nuclide	Type of decay	Half-life	Average emitted energy per transformation		
			Alpha energy, MeV	Beta energy, MeV	Gamma energy, MeV
Uranium-235 ^{235}U ⇓	α	$7.04\ 10^{6}$ y	4.47	0.048	0.154
Thorium-231 ^{231}Th ⇓	β	25.52 h	–	0.163	0.026
Protactinium-231 ^{231}Pa ⇓	β	$3.28\ 10^{4}$ y	5.04	0.063	0.048
Actinium-227 ^{227}Ac ⇓	α (1.38%) + β (98.6%)	21.77 y	0.069	0.016	–
* Thorium-227 ^{227}Th (98.6%) +	α	18.72 d	5.95	0.046	0.106
Francisum-223 ^{223}Fr (1.38%) ⇓	β	21.8 m		0.391	0.059
Radium-223 ^{223}Ra ⇓	α	11.43 d	5.75	0.075	0.133
Radon-219 ^{219}Rn ⇓	α	3.96 s	6.88	–	0.058
Polonium-215 ^{215}Po ⇓	α	$1.78\ 10^{-3}$ s	7.52	–	–
Lead-211 ^{211}Pb ⇓	β	36.1 m	–	0.454	0.053
Bismuth-211 ^{211}Bi ⇓	α (99.7%) + β (0.28%)	2.14 m	6.68	–	0.047
* Polonium-211 ^{211}Po (0.28%)	α	0.516 s	0.021	–	–
* Tallium-207 ^{207}Tl (99.7%) ⇓	β	4.77 m		0.492	
Lead-207 ^{217}Pb		Stable			

* Branched decay

Table 7.
Thorium-232 series (ICRP 1983)

Nuclide	Type of decay	Half-life	Average emitted energy per transformation		
			Alpha energy, MeV	Beta energy, MeV	Gamma energy, MeV
Thorium-232 ^{232}Th ⇓	α	1.405 10^{10} y	4.07	0.013	–
Radium-228 ^{228}Ra ⇓	β	5.75 y h	–	0.0173	–
Actinium-228 ^{238}Ac ⇓	β	6.15 h		0.460	0.930
Thorium-228 ^{228}Th ⇓	α	1.9131 y	5.49	0.020	–
Radium-224 ^{224}Ra ⇓	α	3.66 d	5.78	0.002	0.098
Radon-220 ^{220}Rn ⇓	α	55.6 s	640	–	–
Polonium-216 ^{216} Po ⇓	α	0.145 s	6.91	–	–
Lead-212 ^{212}Pb ⇓	β	10.64 h	–	0.175	0.148
Bismuth-212 ^{212}Bi ⇓	α (35.94%) + β (64.06%)	60.55 m	2.22	0.469	0.185
* Polonium-212 ^{212}Po (64.06%)	α	0.30 µs	5.73	–	
* Tallium-208 ^{208}Tl (35.94%) ⇓	β	3.07 m	–	0.212	1.208
Lead-208 ^{218}Pb		Stable			

* Branched decay

Table 8.
Potassium-40 (ICRP 1983)

Nuclide	Type of decay	Half-life	Average emitted energy per transformation		
			Alpha energy, MeV	Beta energy, MeV	Gamma energy, MeV
Potassium-40, ^{40}K ⇓	β + γ	1.28 109 y	–	0.523	0.156
Argon-40, ^{40}Ar and		Stable			
Calcium-40, ^{40}Ca		Stable			

* Branched decay

ISBN 91-89230-00-0