

# Prevention measures against radiation exposure to radon in well waters: analysis of the present situation in Finland

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## ABSTRACT

Naturally occurring radioactive elements are found in all groundwaters, especially in bedrock waters. Exposure to these radioactive elements increases the risk of cancer. The most significant of these elements is radon which, as a gas, is mobile and dissolves in groundwater. In Finland, water supply plants are obliged to carry out statutory monitoring of the water quality, including radon. Monitoring of private wells, however, is often neglected. In this paper, we outline the problem by reviewing the outcomes of the studies conducted in Finland since the 1960s. We also summarise the development of legislation, regulations and political decisions made so far that have affected the amount of public exposure to radon in drinking water. A review of the studies on radon removal techniques is provided, together with newly obtained results. New data on the transfer of radon from water into indoor air are presented. The new assessments also take into account the expanding use of domestic radionuclide removal units by Finnish households.

**Key words** | groundwater, radioactivity, radon, public communication, water policy, water treatment

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## ABBREVIATIONS AND NOTATIONS

Bq	Becquerel. Unit of radioactivity, equal to one nuclear transformation per second.
Bq/l	Becquerel per litre.
GAC	Granular activated carbon.
Sv	Sievert. Unit of equivalent dose or effective dose equal to $\text{Jkg}^{-1}$ .
man Sv	man Sievert. Unit of collective effective dose, equal to the sum of effective doses of individuals among a group.

## INTRODUCTION

In a modern society, access to high-quality household water and appropriate sewerage and waste water treatment is a necessity that affects the everyday life of its citizens and their means of livelihood, thus making it a service of general interest. A variety of contaminants, such as

micro-organisms, organic and inorganic compounds, and radionuclides can occur in household water and thus lead to health risks unless water reserves, water treatment methods and the materials of water mains and pipes are selected and maintained appropriately. Surveillance of water quality and proper waste water treatment are especially challenging in sparsely populated rural areas where water distribution networks have not been built and people have to pump their household water from private wells.

Naturally occurring uranium has been present in terrestrial matter since the formation of the Earth. Uranium is widely distributed in the Earth's crust and can be found at low levels in all rocks, soils and water. As uranium decays it forms a successive chain of decaying radioactive elements known as the uranium series (Figure 1). The bedrock of Finland is largely composed of igneous and metamorphic rocks, more specifically granite as well as granitoid, migmatite and gneiss complexes (Korkka-Niemi 2001). Rapakivi granite and granite, which make up large areas

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Uranium-238 → Thorium-234 → Protactinium-234 m → Uranium-234 → Thorium-230 → Radium-226 → Radon-222 → Polonium-218 → Lead-214 → Bismuth-214 → Polonium-214 → Lead-210 → Bismuth-210 → Polonium-210 → Lead-206 (stable)

**Figure 1** | The uranium series.

of bedrock, especially in southern Finland, contain high concentrations of uranium. Therefore, bedrock water in these areas may also contain high concentrations of other radionuclides found in the uranium series (Lahermo & Juntunen 1991). In terms of radiation dose, the most significant of these radionuclides is radon-222, which accounts for 71% of the effective dose received by users of drilled wells and 64% of that received by users of dug wells (Table 1). Apart from polonium-210, which accounts for 11% of the effective dose among users of drilled well water, doses from the rest of the nuclides are generally low (Vesterbacka *et al.* 2005, 2006).

In this paper we focus on radon, firstly, because in terms of dose it is the most significant of the naturally occurring radionuclides in drinking water. Secondly, new data are now available on the number of users of private wells and on the transfer of radon from water to indoor air in an average Finnish house. With these new data we are able to assess doses and cancer risks associated with use of well water in more detail. An average detriment from the inhalation of radon released from water was found to be about equal to that from ingestion. Here, we also summarise the development of legislation, regulations and political decisions made so far that have affected the amount of public exposure to radon in drinking water. A review of

the outcomes of removal studies is provided, together with newly obtained results. The new dose assessments also take into account the expanding use of domestic radon removal units by Finnish households.

## SURVEYING RADON IN DRINKING WATER

Systematic surveys of the occurrence of radon in Finnish groundwaters began at the end of the 1960s. In the first phase, 66 bedrock water samples from drilled wells in the Helsinki area were surveyed (Kahlos & Asikainen 1973). Radon concentrations were generally high, with a mean of 1,600 Bq/l, which prompted the surveying of waterborne radon throughout Finland. By the end of 1978, in total 735 samples of tap water from public water supply plants using both surface and groundwaters, 690 samples from dug wells and springs and 878 samples from drilled wells had been measured. The mean radon concentrations in groundwater wells and bedrock water wells were 60 and 630 Bq/l, respectively (Asikainen & Kahlos 1980).

After the end of the 1970s, the surveys were mainly directed at private wells, although all new groundwater sources were assessed before they were connected to the water distribution networks. Bedrock wells were

**Table 1** | Mean concentrations of naturally occurring radionuclides in water from Finnish drilled wells and dug wells and assessed mean annual effective doses, accordingly (Vesterbacka *et al.* 2005, 2006)

Radionuclide	Drilled wells		Dug wells	
	Mean concentration (Bq/l)	Mean effective dose (mSv/a)	Mean concentration (Bq/l)	Mean effective dose (mSv/a)
Rn-222	460	0.29	50	0.032
U-238	0.26	0.008	0.015	0.0005
U-234	0.35	0.014	0.020	0.0008
Ra-228*	0.030	0.017		
Ra-226	0.050	0.010	0.016	0.003
Pb-210	0.040	0.022	0.013	0.007
Po-210	0.048	0.046	0.007	0.007

\*From Vesterbacka *et al.* (2006).

particularly studied in the risk areas where concentrations of radon, uranium or other natural radionuclides had been found high (Salonen 1988). Municipal health inspectors had an important role in surveying radon in private wells: water samples were measured at regional laboratories and sent to the Radiation and Nuclear Safety Authority (STUK) for more detailed analysis if the measured radon concentration exceeded 300 Bq/l. Private wells were also investigated in co-operation with Geological Survey of Finland and the Finnish Environment Institute, which performed nationwide studies on the physico-chemical and microbiological quality of well waters (Juntunen 1991).

In a more recent population-based random study, in which 184 water samples from dug wells and 288 from drilled wells were analysed, the observed mean concentrations of radon were 50 and 460 Bq/l, respectively (Vesterbacka *et al.* 2005). In dug wells, all measured radon concentrations were below 1,000 Bq/l, but 10.8% of drilled wells exceeded this level. The availability of water services has steadily increased during the past three decades, especially in the more densely populated southern Finland, where the highest radon concentrations are also generally found. Today, over 93% of people in southern Finland have access to water distribution services, which could explain the lower mean obtained in the most recent study.

At present, STUK's database contains information on more than 7,600 drilled wells and 3,800 dug wells. Over 50,000 results from the analysis of radon, uranium, radium-226, radium-228, lead-210 and polonium-210 have been recorded. The basic data on the wells includes parameters such as well type, commissioning year, location, depth, purpose of use, annual duration of use, number of users and installed water treatment units. The database is very useful in planning new research projects dealing with topics such as epidemiology, radiation hygiene or water treatment methods.

Finland presently has a population of 5.3 million, about 4.8 million of whom have access to water distribution services (Isomäki *et al.* 2007). All water distributors that service water to more than 50 people are recorded in a national database and all water supply plants and beverage companies are required to comply with statutory monitoring of water quality (Lapinlampi & Raassina 2002). About 500,000 people use private wells or have formed

small local co-operatives for abstracting groundwater. These people typically live in one-family houses in sparsely populated rural areas where municipal water networks are still unavailable, or they are often impracticable to build owing to the long distances to water mains and low end-point consumption. The number of drilled wells has steadily increased. In the 1950s, one well out of 1,000 was a drilled well, but by the early 1990s the portion had increased to 23% (Korkka-Niemi 2001). According to a survey conducted in 2007, the portion of drilled wells was already 32.5% (Vienonen 2007). At the end of 2006, 996,000 households with a total of 2.65 million residents were living in one-family houses (Statistics Finland 2007a). The average number of persons living in one-family houses is thus 2.66. From these data, we can estimate that about 160,000 people permanently use water from drilled wells and that the number of drilled wells in permanent use is about 61,000. The number of summer cottages is presently 475,000, and in nearly half of them water is derived from a private well (Statistics Finland 2007b). These dwellings, however, are used only during the vacations and weekends, and the usage of well water is thus typically limited to less than two months per year.

## LEGISLATION

The preparation of legislation concerning water resources and steering of its implementation are divided between three ministries in Finland: the Ministry of Social Affairs and Health is responsible for the health aspects of drinking water, the Ministry of Environment for waste water discharges and the Ministry of Agriculture for the management of water resources. According to the Radiation Act (592/1991), STUK issues general instructions, known as Radiation Safety Guides (ST Guides), that regulate the use of radiation and operations involving radiation.

### Regulations concerning radon in drinking water

In order to reduce the harmful effects emerging from radioactivity in drinking water, legislation covering both water supply plants and private wells has been passed on national and European Union levels. In Finland,

the Radiation Safety Guide ST 12.3, Radioactivity of Household Water, was passed in 1993 by STUK. It concerns water supply plants and manufacturers of bottled beverages using their own water supply. The objective of Guide ST 12.3 is to limit the effective dose from radionuclides in drinking water to less than 0.5 mSv per year, and its implementation is assessed by an activity index that is calculated from activity concentration measurements of radon, gross alpha and gross beta activity. If the index exceeds a reference value, a more detailed analysis of radionuclides is required. The EU Drinking Water Directive (Council Directive 98/83/EC) introduced another screening parameter, the total indicative dose (TID), by which the effective dose from drinking water was limited to 0.1 mSv per year. The TID corresponds to the annual dose received from all the natural and artificial radionuclides in water except for tritium, potassium-40 and radon, along with its decay products. Its monitoring frequencies were to be set later. However, this work is not finished as of November 2009, and the Commission is currently preparing a revision of the directive. According to recommendation 2001/928/Euratom by the European Commission, the radon concentration in water from water supply plants shall not exceed 100 Bq/l but “a level higher than 100 Bq/l may be adopted if national surveys show that this is necessary for implementing a practical radon programme. For concentrations in excess of 1,000 Bq/l, remedial action is deemed to be justified.” Moreover, an action level of 1,000 Bq/l shall be used for private wells (European Commission 2001).

Decree 401/2001 by the Ministry of Social Affairs and Health recommends water supply plants distributing drinking water in a lesser amount than 10 m<sup>3</sup> per day or to less than 50 persons to limit radon in drinking water below 300 Bq/l. For private wells the recommended maximum concentration is 1,000 Bq/l. The municipal health authority can require an investigation of a private well in the case of a suspected health risk. The municipal health authority is obliged to ensure that households and companies relying on their own water supply receive enough information on the quality and the associated health risks of the local drinking water and on the possibilities of mitigating those risks.

Radon is, thus, included in regulations that concern drinking water from water supply plants and beverage

manufacturers, but also water from private wells. Private well owners are under the supervision of municipal health authorities and, as will be shown in the following sections, this supervision still requires elaboration.

### Legislation concerning organizing water services

The Act on Water Services 2001/119 aims to ensure water services for Finnish citizens by obliging municipalities to draw up sufficient development plans for their territories in co-operation with the water supply plants. When required due to health considerations, a municipality must ensure that appropriate measures are taken to establish a water supply plant to meet the needs, to expand the area of operation or to otherwise secure the availability of sufficient water services. In addition, properties in operational areas of water supply plants must be connected to the existing water distribution network and sewer system. This has expedited the expansion of water distribution networks and the use of their water. Starting from 2005, municipalities and home-owners are entitled to apply for government subsidies to organise water services on the basis of Government Act 686/2004. The amount of the subsidy is up to 50% if the work is carried out by a private or municipal constructor and up to 75% if the government commissions the work. Subsidies can be paid to home-owners for joining water distribution networks, but they may also be given for acquiring water service equipment intended for removing radionuclides from drinking water.

Government Decree 542/2003 on Treating Domestic Wastewater in Areas outside Sewer Networks sets strict requirements for domestic waste water systems that should be met before 2014. According to the Government Programme of Prime Minister Matti Vanhanen's second Cabinet (Prime Minister's Office 2007), the government will channel additional funds to finance water projects in rural areas in an attempt to connect sparsely populated areas to water distribution networks and sewer systems, and involve them in integrated waste management projects in order to comply with Government Decree 542/2003. The recent political decision-making thus promotes the joining of water distribution networks, which will most likely reduce the number of households dependent on private wells in the future.

## FINNISH HOUSING

More than half of Finns (56%) have aspirations towards living in a privately owned one-family house. The majority of Finns prefer housing in sparsely built-up areas and only a quarter desire to live in cities, towns or municipal centres. Families with children, in particular, appreciate peaceful neighbourhoods; about 40% of them wish to live in the countryside (Statistics Finland 2007c). During the past two decades, the proportion of Finns living in one-family houses has remained at 50%. Due to the declining number of persons per household, the absolute number of one-family houses has increased from 820,000 to nearly one million. During the first decade of the twenty-first century, the number of new planning permissions for one-family houses per year has steadily increased. New one-family houses are being built especially in rural areas, since the real estate prices in cities are high, and in the greater Helsinki area over 100% higher than in the rest of the country (Statistics Finland 2008a). Not all sites with planning permission have water mains in the area.

Most one-family houses are owned by the residents. The inclination of Finns towards owning their homes can be explained by the generally acknowledged fact that in Finland, owner-occupied housing has the lowest housing costs in the long term. This is partly due to Finnish fiscal legislation, which allows 28–30% tax deductions on mortgage interest. People aged 18–39 years buying their first home are exempted from the 1.6–4% transfer tax (Ministry of Finance 2005). It is also possible to apply for collateral security from the state up to 20% of the loan. In 2006, more than 70% of Finns lived in owner-occupied houses.

## RADIOACTIVITY MEASUREMENT SERVICES FOR DRINKING WATER

There are about 40 regional laboratories committed to measuring radioactivity in foodstuffs in the case of a fallout situation according to STUK's instructions. STUK provides these laboratories with similar NaI-type gamma spectrometers and organises training and validation for the measurements. Most of these laboratories also use the spectrometers for measuring radon in drinking water.

If the measured radon concentration exceeds 1,000 Bq/l, the regional laboratories advise the customers to send a water sample to STUK for more comprehensive analysis. Well-owners or municipal health officers can also send water samples directly to STUK for analysis.

If the second measurement confirms the radon concentration to be higher than 1,000 Bq/l, the customer is advised to consider remedial action. The principle alternative is to join a water distribution network. This, however, is not always possible, and purchasing a radon removal unit may therefore remain the only viable option. Before buying a treatment unit, the occurrence of other natural radionuclides is screened by gross alpha and gross beta activity measurement and analysis of certain water quality parameters is recommended. Sometimes, water contains primary (health) contaminants, e.g. uranium, fluoride or arsenic, or secondary (technical-aesthetic) contaminants such as iron, manganese or humic substances that should be removed together with radon.

## HEALTH EFFECTS OF RADON

Both ingestion and inhalation of radon increases the cancer risk. For individual tissues or organs the dosimetric quantity used is the equivalent dose, and for the whole body the effective dose, which is the sum of the weighted equivalent doses for all organs and tissues. The unit of both is the sievert (Sv). The collective effective dose describes the sum of effective doses among a group of individuals and its unit is the man sievert (man Sv). The cancer risk for a long-term exposure of one sievert effective dose has been estimated at 5.5% for the whole population and 4.1% for adult workers (ICRP 2007). Stochastically, this would mean that if a person is exposed to an effective dose of one sievert during a long period of time, the individual risk of cancer is increased by 5.5 percentage points. If the same dose is distributed among a hundred people, the risk that one of them gets cancer would still be increased by 5.5 percentage points. For an individual, the increase would then be only 0.055 percentage points. There are, however, limitations when using these radiation-related cancer risk coefficients, which are based on epidemiological data on medium and high doses. Large uncertainties may be related to their use in

the low dose range, and the calculation of radiation-related cancer risk from a collective dose that is comprised of small individual doses or doses ranging over several orders of magnitude is not justified. For collective effective doses that are smaller than the reciprocal of the risk coefficient (i.e. 18 man Sv), the number of excess cancer cases is most probably zero (NCRP 1995).

### Ingested radon

The National Research Council has evaluated risks from ingested radon and has assessed equivalent doses for different organs and tissues (NRC 1999). The highest equivalent dose is caused to the stomach walls, and about 80% of the cancers related to ingested radon are estimated to be stomach cancers. The effective dose per unit intake of ingested radon is estimated to be  $3.5 \cdot 10^{-9}$  Sv/Bq for adults. The dose per unit intake increases with decreasing age: for five-year-old children the factor is estimated to be  $1.0 \cdot 10^{-8}$  Sv/Bq and for infants  $4.0 \cdot 10^{-8}$  Sv/Bq.

In order to assess the doses from the intake of well water we must first know the amount of well water consumed. Water used for preparing food or hot beverages contains no radon, since radon is released from water when boiled (Abulfaraj & Mamoon 1995). Drinking water consumption has been investigated among the adult Finnish population in the age groups 25–34, 35–44, 45–54, 55–64 and 65–74 years. The average daily intakes among female and male populations representing these age groups were 0.667–0.929 and 0.441–0.676 litres, respectively (Paturi *et al.* 2008). No data are available on water intake among children. The closest country from which these data are available is Germany. There, water intake (mineral water and tap water) among age groups 2–3 years and 4–8 years was 0.175 and 0.215 litres per day, respectively (Sichert-Hellert *et al.* 2001). In the age group 9–13 years, boys consumed 0.344 and girls 0.298 litres per day. Packaged waters normally have long storage times and, owing to the relatively short half-life of radon, contain little radon. Until now, the consumption of packaged water has been very low in Finland: in 2004 the per capita consumption was only 14.1 litres per year (Gleick 2006).

Naturally, not all drinking water is consumed at home: water is also consumed at day-care centres, schools, work

places, cafeterias and other places. The proportion of children attending day care is higher in older age groups, being 36.6% on average among 0- to 6-year-olds. The average number of days in day care is 175 per year (STAKES 2008). All children aged between 7 and 15 attend school and the mean number of school days per year is 188. The average number of days at work per year is 220 for those who are employed. The proportion of pensioned or unemployed people increases with age (Statistics Finland 2008b). Among the elderly, days spent in nursing homes or hospitals increases with age: 5 day per year among the age group 65–74 years, 26 among 75- to 84-year-olds and 97 among people older than 85 years (STAKES 2008). People also spend time travelling and at summer houses. People from rural municipalities travel about 19% less than the national average and families with children make about 20% more domestic trips than the average population. Travelling is most common among the age group 25–34 years, being 29 nights per year spent outside the home (Statistics Finland 2007d).

We assumed that two-thirds of water is consumed at home on day-care/school/work days, and no well water is consumed on days spent travelling and at nursing homes or hospitals. In addition, data on the missing age groups were interpolated or extrapolated when assessing the water intake among different age groups (Tables 2 and 3). The age-weighted mean effective doses received from the ingestion of drilled well water by females and males were calculated as 0.35 and 0.26 mSv/year, respectively. Respective effective doses received by users of dug well water are 0.04 and 0.03 mSv/year, respectively. Among users of water where radon exceeds 1,000 Bq/l, the mean radon concentration is 2,700 Bq/l and the effective doses from ingestion for female and male users are 2.0 and 1.5 mSv/a.

Next, we assess the detriments related to ingested radon for different users of drilled wells. Life expectancy at birth of female and male Finns is 75.8 and 82.8 years, respectively. If a person uses drilled well water that contains 2,700 Bq/l of radon throughout life, the risk of having cancer is 0.9 and 0.6% among female and male users, respectively. It is, however, rare that a person lives in the same house for his or her entire life. According to Strandell (2005), people from the age group 20–29 years live in one-family houses substantially less often than those from other age groups. This is easily explained by young adults moving away from

**Table 2** | Assessed water intake among the Finnish female population

Age (years)	No.-female ( × 10 <sup>3</sup> )	Water intake (l/d)	Day-care/school/work (d/y)	Hospital/nursing home/travelling (d/y)	Intake of well water (l/y)
0	29	0.025	13	20	9
1	28	0.120	54	20	39
2–3	56	0.175	87	20	55
4–8	139	0.215	154	20	63
9–13	155	0.298	188	20	84
14–17	130	0.639	203	22	174
18–24	224	0.929	206	23	254
25–34	315	0.929	202	24	255
35–44	350	0.850	198	21	236
45–54	382	0.709	190	20	200
55–64	365	0.755	126	19	230
65–74	252	0.667	6	20	229
75–84	195	0.667	0	37	219
≥ 85	71	0.667	0	103	175

their childhood home and studying in towns or cities. As mentioned above, families with children generally value living in the countryside and buy their house when the parents are around 30 years old. The mean age of women at first birth was 28.0 in 2006 (STAKES 2007). Therefore, we also present estimates of detriments among age groups 0–18 and 30–82/75 years (Table 4).

We can estimate that the collective effective dose is 31 man Sv annually among users of drilled well water in

which radon exceeds 1,000 Bq/l. This translates into approximately two cancers attributable to ingested radon. For the users of drilled well water in which the radon concentration is lower than 1,000 Bq/l, the collective effective dose is roughly 19 man Sv per year and among users of dug wells 11 man Sv, so radiation-related health effects among these groups should theoretically be even less.

In the latest survey, only 30 water samples exceeded the guideline value of 1,000 Bq/l. Extreme concentrations of

**Table 3** | Assessed water intake among the Finnish male population

Age (years)	No.-male ( × 10 <sup>3</sup> )	Water intake (l/d)	Day-care/ school/work (d/y)	Hospital/nursing home/travelling (d/y)	Intake of well water (l/y)
0	30	0.025	13	20	9
1	29	0.120	54	20	39
2–3	59	0.175	87	20	55
4–8	146	0.215	154	20	63
9–13	161	0.344	188	20	97
14–17	136	0.518	203	22	150
18–24	235	0.633	206	23	185
25–34	331	0.633	202	24	185
35–44	362	0.536	198	21	164
45–54	385	0.448	190	20	160
55–64	358	0.429	126	19	142
65–74	213	0.429	6	20	151
75–84	115	0.429	0	37	145
≥ 85	23	0.429	0	103	115

**Table 4** | Mean detriments related to ingested radon among different well water users groups

Group		Detriment, whole life	Detriment, age 0–18	Detriment, age 30–*
Female	Drilled wells	0.16%	0.03%	0.11%
	Drilled wells (Rn > 1,000 Bq/l)	0.92%	0.17%	0.61%
	Dug wells	0.02%	0.003%	0.01%
Male	Drilled wells	0.11%	0.03%	0.07%
	Drilled wells (Rn > 1,000 Bq/l)	0.64%	0.16%	0.37%
	Dug wells	0.01%	0.003%	0.007%

\*30–refers to females aged 30–82 years and males aged 30–75 years.

radon in well water are, however, occasionally found. In summer 2007, two well waters containing 62,000 and 130,000 Bq/l of radon were measured. The latter family had been using the water regularly for a period of 10 years. The effective dose from ingested radon to the five family members was about 1 Sv each, so it can be estimated that the risk of one of the family members getting cancer attributable to ingested radon is about 30%. Presently, 129 wells with water exceeding 10,000 Bq/l have been found in Finland.

### Radon released into indoor air

Normally, the most significant source of radon in indoor air is the soil beneath the house. In Finnish one-family houses, the average radon concentration in indoor air is 145 Bq/m<sup>3</sup> (Arvela *et al.* 1993). Other sources include building materials and household water. Because radon is a gas and has a solubility in water similar to carbon dioxide, it is partly released into indoor air during water usage. The proportion of radon released from water during certain types of water usage (e.g. shower, toilet) is expressed as a transfer coefficient. By measuring indoor-air volume of the house  $V$ ; the air-exchange rate of indoor air  $\lambda$ ; the use-weighted transfer coefficient  $e$ ; and the water consumption rate  $W$ , we can calculate the transfer factor  $f = We/V\lambda$ , by which the amount of waterborne radon released to indoor-air can be assessed (Nazaroff *et al.* 1987). Water usage by Finnish households has been well investigated and the average water usage in one-family houses has been defined as 125 litres per person per day. The largest share of the water is used for showers (39%), drinking and cleaning (27%) and the toilet (14%) (Etelämäki 1999). From transfer coefficients reported by Nazaroff *et al.* (1987), we can estimate that the

use-weighted mean transfer efficiency is 0.57. The average living area of Finnish one-family houses is 134 m<sup>2</sup>, and assuming a room height of 2.5 m we can estimate the average volume to be 340 m<sup>3</sup> (Statistics Finland, 2007d). The mean air exchange rate in Finnish one-family houses is 0.64 (Ruotsalainen *et al.* 1992). Using these data we come to a value  $0.36 \cdot 10^{-4}$ , i.e. 1,000 Bq/l of radon in water increases the indoor air radon concentration by 36 Bq/m<sup>3</sup>. It must be noted that large variations in the transfer factor occur because the house dimensions and water consumption rates are highly case-specific.

To validate this value, 268 houses where radon in both drilled well water and indoor air had been measured were randomly selected from STUK's indoor air database. The regression analysis performed on these data indicated that the baseline value for indoor air was 210 Bq/m<sup>3</sup> and the transfer factor was  $0.36 \cdot 10^{-4}$  ( $R^2 = 0.35$ ). By setting the baseline value to the average radon concentration of indoor air in one-family houses (145 Bq/m<sup>3</sup>), we obtain a value  $0.39 \cdot 10^{-4}$  ( $R^2 = 0.33$ ) for the transfer factor.

By applying the transfer factor of  $0.39 \cdot 10^{-4}$  we can estimate that the additional radon concentration in indoor air is 2 Bq/m<sup>3</sup> in houses with dug wells and 18 Bq/m<sup>3</sup> in houses with drilled wells, which are small values compared to the average indoor air concentrations in Finland. The average additional indoor air radon concentration in houses where the recommended maximum value for radon is exceeded is 100 Bq/m<sup>3</sup>.

Breathing radon and its progeny causes an equivalent dose almost exclusively to the lungs, and the prominent detriment is thus lung cancer. The dose is mostly comprised of short-lived radon progeny consisting of metal ions or atoms, which can cluster and attach to indoor air particles.

The aerodynamic diameter of these products determines where in the respiratory system they are deposited. In addition to particle size distribution, the ratio of radon progeny to radon (equilibrium factor) also varies. Assessed effective dose conversion factors for radon in the indoor air of homes range from  $6 \times 10^{-9}$  to  $15 \times 10^{-9}$  Sv/(Bq h m<sup>-3</sup>) (UNSCEAR 2000). STUK has chosen to apply a value of  $6 \times 10^{-9}$  Sv/(Bq h m<sup>-3</sup>) with an equilibrium factor of 0.4, as is recommended in ICRP65 (ICRP 1994). Hence, we can estimate that the average effective dose from radon released from water is 0.03 mSv/year among users of dug wells and 0.30 mSv/year among users of drilled wells. Among the users of drilled wells where radon exceeds 1,000 Bq/l the mean effective dose can be estimated as 1.8 mSv/year.

According to a collaborative analysis of data from 13 European case-control studies, the risk of lung cancer increases by 16% per 100 Bq/m<sup>3</sup> of radon in indoor air of homes (Darby *et al.* 2005). The lung cancer incidence in Finland is about 4.2 per 10,000 citizens per year (Finnish Cancer Registry 2007). From these data we can assess that among users of dug wells, lung cancer cases attributable to water usage are likely to be less than one case per year. Among users of drilled wells, about two lung cancers are annually attributable to radon in water.

Summing up the different exposure pathways, we can estimate that radon in private wells causes only a few cancer cases per year in Finland. The main target group for radiation protection is those whose water contains radon in excess of 1,000 Bq/l, which is the recommended maximum concentration for private wells. Among this group, the theoretical number of radon-related cancers is only three per year. Epidemiological studies also support the assessment made above (Auvinen *et al.* 2005; Kurttio *et al.* 2006). In these studies, the risks of stomach, kidney and bladder cancers and leukaemia from the radionuclides ingested with drinking water were assessed using a case-cohort method. The results did not indicate increased risks of any of these four cancers at the exposure levels of the epidemiological study.

### Methods for removing radon from drinking water

Research on radon removal from water supplies was initiated in the 1970s in Czechoslovakia (Hanslik *et al.* 1978). Aeration was found to be a suitable method for

stripping radon gas out of water. A removal efficiency of 99% was recorded for 8 minutes aeration time and an air-to-water ratio of 1: 8. In the early 1980s, different aeration techniques and activated carbon adsorption were tested in Sweden. Aeration under atmospheric pressure was reported to be a viable method, with a removal efficiency of up to 75% (Hedberg *et al.* 1982). In the USA, studies were also begun in the early 1980s (Lowry 1983). Three methods were tested and found effective: granular activated carbon (GAC) adsorption, diffused aeration and spray aeration. Initially, GAC adsorption was considered the most auspicious method due to its effectiveness and low investment and maintenance costs. After a few years the viability of GAC adsorption was re-evaluated due to external gamma radiation caused by the units and waste problems emerging from spent GAC batches (Rydell *et al.* 1989).

Removal studies in Finland began in the early 1990s by first reviewing the literature on the viable treatment methods (Jokela 1993). Experimental studies were initiated a couple of years later in collaboration between STUK, the Finnish Environment Institute and Helsinki University of Technology. From the first project onwards, the main objective has been to bring suitable and reliable treatment units to the market so that home-owners can easily purchase them. Therefore, companies specializing in water treatment have been invited to participate in the research projects (Myllymäki 1996; Myllymäki *et al.* 1999).

In 1997, a new research project was initiated within the 4th Framework Programme financed by the European Commission. Seven institutions from four member countries participated in a project in which removal of the most commonly occurring natural radionuclides (radon, uranium, radium-226, lead-210 and polonium-210) from groundwaters was investigated (Annamäki & Turtiainen 2000). Water works were also included in the research (Salonen *et al.* 2002). After the project, dozens of removal units were in use in Finnish homes. In order to obtain long-term experiences of their operation, a follow-up project was initiated and the units were monitored until the end of 2002 (Vesterbacka *et al.* 2003). At this time, a few hundred units had been installed and problems associated in their use had been recognized. The companies involved in the projects had gained expertise and most of the consumer guidance can now be channelled there.

### Granular activated carbon adsorption

As a non-polar monatomic gas, radon is effectively adsorbed on activated carbon. Granular activated carbon filters sold in Finland are typically pressure vessels with carbon bed volumes of 39–105 litres. An automatic backwash system is employed in cases where the influent contains large amounts of iron, manganese or humic substances. These filters are always installed to treat all household water so that exposure to radon through inhalation is also prevented. The units operate passively under normal plumbing pressure (2–6 bar) and therefore do not require additional pumps. This keeps the acquisition price of the unit low compared to the aeration technique (Turtiainen *et al.* 2000a).

The amount of radon accumulated in the unit depends on the water usage and the radon concentration in raw water. The short-lived progeny of radon that emit gamma radiation are also retained on the carbon bed, which thus becomes a source of external gamma radiation. Therefore, GAC filters cannot be installed inside residential buildings and their use should be limited to radon concentrations below 5,000 Bq/l (Annamäki *et al.* 2000).

The radon removal efficiency of GAC filters was followed at ten households for a period of 3 to 9 years. The carbon bed was replaced with a fresh batch in three locations during the follow-up. In the selection of the households, different types of water were covered, including iron- and manganese-rich water and water with a high content of organic carbon. Radon concentrations in raw water were 1,500–7,400 Bq/l (Vesterbacka *et al.* 2003). All GAC filters removed more than 90% of radon, and most of them nearly 100%. Some units showed a decline in removal efficiency over time, and hence to ensure an adequate removal efficiency it was recommended that the carbon batches be replaced every three years. Water quality, both microbiological and chemical, remained good. Iron and organic substances were partly removed by GAC filtration (Turtiainen *et al.* 2000b).

Some equipment designed for iron and manganese removal can be partly filled with activated carbon and thus simultaneously removes iron, manganese and radon (Vesterbacka *et al.* 2003). Iron and manganese removal units that are based on aeration-oxidation normally do not

produce a sufficient amount of air to effectively strip radon and hence cannot be recommended for radon removal (Vesterbacka & Salonen 2008).

### Aeration

As a dissolved gas, radon can be removed from water by aeration. Three alternative principles are customarily employed in aeration: a large number of air bubbles are produced in the water (diffused aeration); water is sprayed into air as small droplets (spray aeration); or a large surface is created between water and air on an inert material (tower aeration) (Annamäki & Turtiainen 2000). Domestic aeration units typically employ a combination of the first two principles and the aeration time needed is 4–10 minutes. Most commercial systems work under atmospheric pressure and hence a water pump and a pressure tank are needed after the aeration unit to give the water enough pressure to deliver it throughout the plumbing (Mjönes 2000). Water flow from a well through an aeration unit into a pressure tank is electronically controlled. The cost of acquiring aeration units is two to three times as high as that of a GAC filter. This difference, however, will be partly compensated by the higher operating costs due to changing the carbon batch every three years (Mäkeläinen & Turtiainen 2003). Low-cost alternatives where aeration takes place in the bore hole have also been introduced (Vesterbacka *et al.* 2003).

In total, aeration units from eight manufacturers have been tested. The lowest radon removal has been recorded for aeration in the bore hole, where efficiencies varied from 3% to 77% (average efficiency during 100 litres flow). More sophisticated aeration units, however, were all able to remove more than 90% of radon. Presently, four brands are available on the Finnish market, all with adequate radon removal efficiency.

### Customer insights on radon removal units

A survey among customers who have bought radon removal units was conducted with a questionnaire (Vesterbacka *et al.* 2003). Activated carbon adsorption was the most prevalent technique of radon removal, with a 70% share. Only 7% reported defects or inconveniences, the most common being difficulty in replacing the carbon batch. By contrast,

more than half of the users of aerator units reported defects or inconveniences. Malfunction in solenoid valves was the most common complaint.

Another survey was conducted in 2008 by a telephone interview. All well-owners who had learned that the radon concentration in their well water exceeded 1,000 Bq/l (53 families) were asked what measures they had taken to reduce the concentration, if any. Already, 32 families had reacted: 19 of them had purchased activated carbon filters, ten families had joined or were joining public distribution networks and three families had acquired aerators. Twelve families were still contemplating the options, while nine families did not intend to react. The latter had radon concentrations ranging from 1,000–4,000 Bq/l. This survey implies that most people are ready to take measures against radon in well water when they receive information.

This is also shown when considering the number of removal units sold. Companies were interviewed and asked how many radon removal units that they had sold. As of in March 2007, this number was about 1,000. According to the latest survey, the number of wells where radon exceeds 1,000 Bq/l is about 6,600, which means that measures against radon have been taken for about 15% of the wells with elevated radon concentrations.

### **Effect of radon removal units on the collective effective dose**

Assuming an average removal efficiency of 95% for the removal units, the effective dose through both ingestion and inhalation of radon has been reduced by 3.4 mSv per year on average among those who have purchased them. Expressed as collective effective dose, the reduction is about 9 man Sv per year. Two uncertainties relating to the assessment reversely affect the amplitude of averted doses: the number of households that have connected to water networks is not known and thus the amplitude of averted doses may be higher. However, a proportion of the removal equipment is used at summer houses, which would suggest that averted doses estimated above may be smaller. If the remaining households that still use water with an elevated radon concentration would take measures to reduce radon, the averted collective effective dose could be about 50 man Sv annually.

### **PUBLIC COMMUNICATION**

As discussed earlier, decree 401/2001 by the Ministry of Social Affairs and Health obliges municipal health authorities to ensure that households relying on their own water supply receive enough information on the quality and the associated health risks of the local drinking water and on the possibilities of mitigating those risks. Far too often, municipal health authorities have failed to do this, as was the case with two high radon concentrations found in summer 2007. In both these cases the residents had not been informed by the municipality about the associated health risk, but had taken the initiative themselves to have their water measured after receiving the information elsewhere. As was shown, the collective effective doses and the associated number of fatal cancers are small, but regarding the ALARA principle of limiting radiation exposure to “as low as reasonably achievable”, counter-measures must be taken in cases where the radon concentration of an individual’s drinking water is high.

During the past decade, STUK has organised courses for municipal health authorities and the personnel of water supply plants on the health risks of radon and removal methods for drinking waters. These have usually been held two or three times per year, and there have generally been a few dozen attendees at the lectures. Considering that there are 415 municipalities in Finland with occasionally changing personnel, the training has therefore been insufficient.

For this reason, STUK sent letters in May 2008 to 67 municipalities where more than 20% of investigated drilled wells contain radon above 1,000 Bq/l. The letters, containing information on the occurrence, measurement and removal of radon, were addressed to health inspectors. Since Finland has two official languages, all materials and information were provided in both Finnish and Swedish. A few days later a press release was published and the list of the municipalities along with statistical information on wells was provided on STUK’s Internet site. This press release was reported in several regional newspapers and on radio stations, which resulted in increased measurement activity in these radon-prone areas.

Statistically, the number of cancer cases related to the consumption of water from wells is only a few per year. However, we feel that Finnish citizens have the right to be

informed about this risk, and this right is also implemented in national legislation. Radiation is a sensitive issue for many families, especially those with children. Therefore, it is important that the work to locate the remaining 5,000 to 6,000 wells with elevated radon concentrations continues.

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