

3.9.7 Laboratory tests

In the laboratory two types of systems were tested for their capability in removing natural radionuclides by using ground water simulants: countertop pour-through filters and domestic water softeners.

Countertop pour-through filters, point-of-use-systems for treating only the small amount of water intended for human consumption, usually consist of a jug, a filter holder and exchangeable filter cartridges. The cartridges are aimed to improve the taste and quality of drinking water. After exhaustion of the filter capacity the cartridges are centrally recycled or disposed with household waste. The aim of the experiments was

- to determine the efficiency of a widely used commercially available filter system for the removal of uranium, radium and lead
- to study the influence of the treatment on other water quality parameters (mineralisation, hygienic quality)
- to modify the filter cartridges to optimise radionuclide removal and to minimise the influence on other water quality parameters.

Two commercially available cartridges and 5 modified cartridges were tested. The commercially available cartridges have not been developed for the special purpose of reducing radionuclides in drinking water. The experiments showed that with modified cartridge fillings radionuclides can be removed more selectively and more efficiently; the influence on the ionic composition of the feed water can be minimised.

Tests simulating the household use of pour-through filters showed that severe deterioration of the hygienic water quality can occur. The exhausted filter cartridges are solid waste with an activity of up to several 100 Bq/g. A summary of the radionuclide rejections achieved with the tested cartridges is set out in Table X.

Table X. Average rejection of radionuclides by pour-through filters.

Filter cartridge	Average rejection of radionuclides (100 L filtered)		
	Ra-226	Pb-210 / Pb	U-nat.
Brita standard	80%	60%	80%
Brita anti-nitrate	80%	95%	90%
SAC/Na	97%	20%	0%
SAC/Ca	95%	20%	0%
SAC/Ca + SBA/Cl	97%	40%	55%
SAC/Ca + NSS/Cl	98%	-	60%
WAC/Ca + SBA/SO ₄	85%	80%	40%

Two typical domestic water softeners, both of them with automatic regeneration, were tested for their capability in removing radium and lead. In detail the aim of the experiments was

- to determine the efficiency of the systems in removing radium and lead
- to study regeneration efficiency and accumulation of the radionuclides on the ion exchange resin over several cycles
- to describe the influence of the treatment on other water quality parameters (ionic composition , hygienic quality).

For the removal of ²²⁶Ra and ²¹⁰Pb the operational mode recommended by the manufacturer for softening was followed. Lead removal was in the range of hardness reduction, from 90% to 95% at the start of a cycle decreasing to about 80% to 90% just before regeneration started. Some cycles with bad reduction showed that the removal of lead is unreliable; small changes in water quality might influence the speciation and cause this variation. ²²⁶Ra reduction exceeded hardness removal, beginning at about 95% and decreasing to about 90% at the end of a cycle. Higher values in the first bed volumes of a cycle were caused by insufficient backwashing of the filter after regeneration.

Simultaneously with ²²⁶Ra and ²¹⁰Pb, Ca and Mg causing hardness of water are almost completely exchanged for Na, resulting in corrosive water. Electrical conductivity and pH was nearly unchanged, a high increase being observed for the heterotrophic plate count. This shows that even with short regeneration intervals a deterioration in hygienic quality cannot be excluded.

The regeneration efficiencies measured were only about 11% for ^{226}Ra and 37% for ^{210}Pb . Due to the limited regeneration efficiency accumulation of ^{226}Ra and ^{210}Pb occurs on the resin. This is not a linear process but a maximum value is reached dependent on feed water concentration, the regeneration interval and regeneration efficiency. A model developed for simulating this process was successfully verified with experimental data.

The use of CaCl_2 was tested for regeneration instead of NaCl to avoid an undesirable reduction in water hardness. Unfortunately, the CaCl_2 crystallised in the salt container and blocked the system. Modifications in the design of the water softeners is necessary to use this alternative.

The waste produced by these systems is used regeneration brine. The volume of this liquid, high in salinity, with a radionuclide concentration of 10 to 30 times the feed value, is in the range from 3% to 10% of the treated water volume.

3.10 Removal of U, Ra, Pb and Po with Adsorptive or Membrane Filters

Methods employing adsorptive filters, reverse osmosis (RO) and nanofiltration (NF) to remove natural radionuclides from drinking water were studied. Part of the study was to investigate if new adsorptive materials can be found and established for the adsorption of the non-volatile elements uranium ($^{238,234}\text{U}$), radium (^{226}Ra), lead (^{210}Pb) and polonium (^{210}Po).

3.10.1 Adsorptive filters (mineral materials)

Mineral materials are known to be selective in removing natural radionuclides from water under various conditions. Depending on the type of material and the compound to be removed different removal processes may be involved. Common to these materials is that they are not yet widely used for the treatment of drinking water.

The two main processes which may take place and which are responsible for the removal of radionuclides by mineral materials are adsorption and ion exchange. Zeolites in particular, which are actually synthetic clay minerals,

act as ion exchangers like ordinary organic resins. Also, hydroxyapatite acts as an ion exchanger.

Adsorption is a phenomenon that takes place at the surface boundary between two phases, a liquid phase (drinking water) and a solid phase (mineral material). Radionuclides can be collected on the surface of the adsorptive material, leading to an enrichment of these substances at the surface. Adsorptive mineral materials are porous and have a rather large surface area (some 100 m²/g adsorbents). When the adsorbent is fully covered, the material has to be replaced.

Spiked water was used in the experiments. The water consisted of deionized water with varying amounts of calcium, magnesium and sodium salts.

After batch experiments with several materials such as zeolites (Na-Y zeolite, Wessalith XD[®] and H-ZSM5 M28), tin dioxide, titanium dioxide, calcium sulphate, barium sulphate and silica gel, two mineral materials, hydroxyapatite and manganese dioxide, were selected for more detailed studies in column experiments as well as a commercially available ion exchange unit (BRITA[®]).

Field experiments were carried out in order to evaluate the effectiveness of hydroxyapatite in removing natural radionuclides under normally occurring conditions. Hydroxyapatite was tested in a pour-through filter.

The laboratory experiments showed that hydroxyapatite has a good capability for adsorbing uranium and radium. The field experiments with very small flow rates showed the same phenomenon. The high adsorption at slow flow indicate that a strong interaction between the feed water and the surface of hydroxyapatite is necessary to gain good results. Therefore a new granular form has to be developed to obtain smaller and perhaps more porous particles to increase the surface area and contact time.

Results of the experiments with manganese dioxide as adsorbent showed that the adsorption yield of uranium decreases with increasing pH value and that the adsorption is smaller if the water hardness is high.

3.10.2 Membrane filters

A membrane can be defined as a thin film separating two phases and acting as a selective barrier to the transport of matter. In membrane operation a feed stream is divided into two streams: a permeate containing material which has passed through the membrane, and a retentate (or concentrate) containing the non-permeating species.

The driving force for the separation is either difference in pressure, concentration, temperature or electrical potential across the membrane. The majority of radionuclides occurring in natural waters (radium and uranium in particular) are not fixed to particles but are dissolved as ions. Therefore only membranes with very small pore sizes ("molecular sieves") are able to remove these radionuclides effectively. Reverse osmosis (RO) and nanofiltration (NF) are pressure-driven membrane processes.

Osmosis occurs when two aqueous solutions of different concentrations are separated by a semi-permeable membrane. Since the osmotic pressures of the two solutions are different and therefore out of balance, water will flow from the solution of lower concentration, through the membrane, to dilute the solution having higher concentration. The transport of water increases the osmotic pressure of the dilute side, while reducing the osmotic pressure on the concentrate side. Eventually permeation (water flow) will cease, and the system will be in balance.

RO is the reversal of this natural process. By applying pressure (exceeding the difference of osmotic pressure) on the more concentrated solution in contact with the membrane, the feed water is divided in a permeate with low salt concentration passing the membrane (product water) and the concentrated solution, called retentate (waste water). The particle size range for applications of RO is approximately 0.1 nm to 1 nm; the mechanisms of separation of species are based on processes relating to their size and shape, their ionic charge and their interactions with the membrane itself.

NF is similar to RO and is applied in the area between the separation capabilities of RO membranes and ultrafiltration (UF) membranes. NF systems typically operate at lower pressures than RO but yield higher flow rates of water despite the different quality of RO. NF is used when high sodium rejection, typical of RO, is not needed, but where other salts such as Mg or Ca (i.e. divalent and higher valent ions, also the natural radionuclides

concerned) are to be removed. The basic principles for the NF operation are the same as for RO.

Five different reverse osmosis (RO) and nanofiltration (NF) systems, typical of the great number of commercially available ones, were tested in the laboratory. Three of them were POU-RO units, one a POE-RO unit and one a POE-NF device (POU: point-of-use, POE: point-of-entry). Except for the last one, all of them are commercially available. Two different RO units were studied in the field. The units were installed for test purposes only and the water was not used as drinking water. Both of the units were POU-RO units. The practicability of the membranes was studied for a period of seven months.

In NF experiments at a plate module pilot plant the five most important uranium species for the mobilisation of uranium in natural water, UO_2CO_3^0 , $\text{UO}_2(\text{CO}_3)_2^{2-}$, $\text{UO}_2(\text{CO}_3)_3^{4-}$, $\text{UO}_2(\text{HPO}_4)_2^{2-}$ and UO_2^{2+} were generated in different model waters. Their rejection was determined at six NF membranes, which represent a broad spectrum of commercially available NF membranes, and at two open reverse osmosis (RO) membranes.

The single operational unit into which membranes are engineered for use is referred to as a module. The module consists of the membranes, pressure support structures, feed inlet and concentrate outlet ports and permeate draw-off points. For RO and NF two major types of modules are found on the market: the spiral wound and the hollow fibre type.

The common membrane materials are cellulose acetate (spiral wound), polyamide (hollow fibre, spiral wound) and thin film composites. Cellulose acetate membranes are chlorine tolerant, more tolerant to foulants than others but with an increased danger of biological attack, especially with warm feeds. Better salt rejection but no chlorine tolerance are characteristics of polyamide membranes. Thin film composites have the best performance (high flux at low pressure, high salt rejection, not biodegradable) but their tolerance to fouling is lower than cellulose acetate.

Expected problems with the use of RO or NF systems for drinking water treatment are demineralisation and pH-lowering, resulting in a lack of essential minerals for human health, corrosiveness of the water and infraction of drinking water regulations and deterioration in hygienic quality.

3.11 Speciation of U, Ra, Pb and Po in Water

The aim of this study was

- to make a literature survey of speciation of U, Ra, Po and Pb in ground waters
- to determine ^{210}Po and ^{210}Pb in particles in ground waters
- to determine the oxidation states of uranium in ground waters.

A literature survey on speciation and the behaviour of uranium, radium, lead and polonium in ground waters was performed. As a result of this literature survey and due to the first experimental results obtained from other studies made in the TENAWA project, it became evident that most information was needed on the speciation of lead and polonium in ground water. For this reason the speciation of these two radionuclides was chosen for more detailed investigation. As the second step of this study the division of ^{210}Po and ^{210}Pb in ground water into soluble and particle-bound fractions of different size was studied.

The ground water samples were taken from four different locations, which were previously known to contain high concentrations of natural radionuclides. The ground water samples were filtered with five membranes with pore sizes ranging from $0.8\mu\text{m}$ to 5 kD and retention of ^{210}Po by these membranes was determined. The same was done for ^{210}Pb with three membranes with pores between $0.45\mu\text{m}$ and 5 kD. The percentage proportions of ^{210}Po and ^{210}Pb bound in various particle fractions are given in Figure 7 and 8.

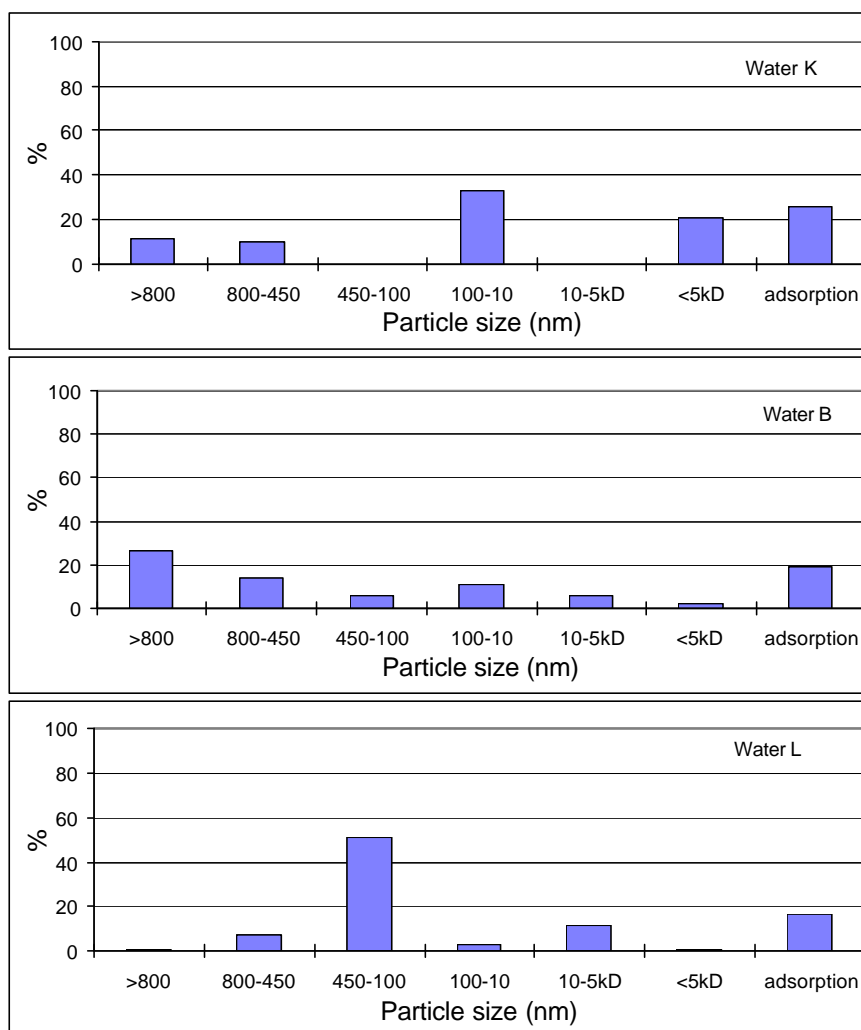


Figure 7. Percentage proportions of ^{210}Po in the total activity bound in various particle size fractions from ground waters K, B and L.

In waters B and I ^{210}Po and ^{210}Pb are mainly bound in particles with sizes greater than $0.45\ \mu\text{m}$, especially in water I this fraction containing ^{210}Pb comprises more than 80% of total activity. In water L and K, however, the intermediate size fraction, around $0.1\ \mu\text{m}$, containing ^{210}Pb is prevalent. ^{210}Po in these waters is more evenly distributed in various particle size fractions (Figures 7 and 8). Only in one water (water K), with relatively high NaCl concentration and rich in humus material, was a considerable fraction, about 20% of both radionuclides found to be present in the soluble form, i.e.

passing through the membrane with the smallest pore size (5 kD). It was also found that large fractions of both radionuclides were adsorbed in the filtration system, filters and vessels. The fractions adsorbed on filters are also shown in these figures.

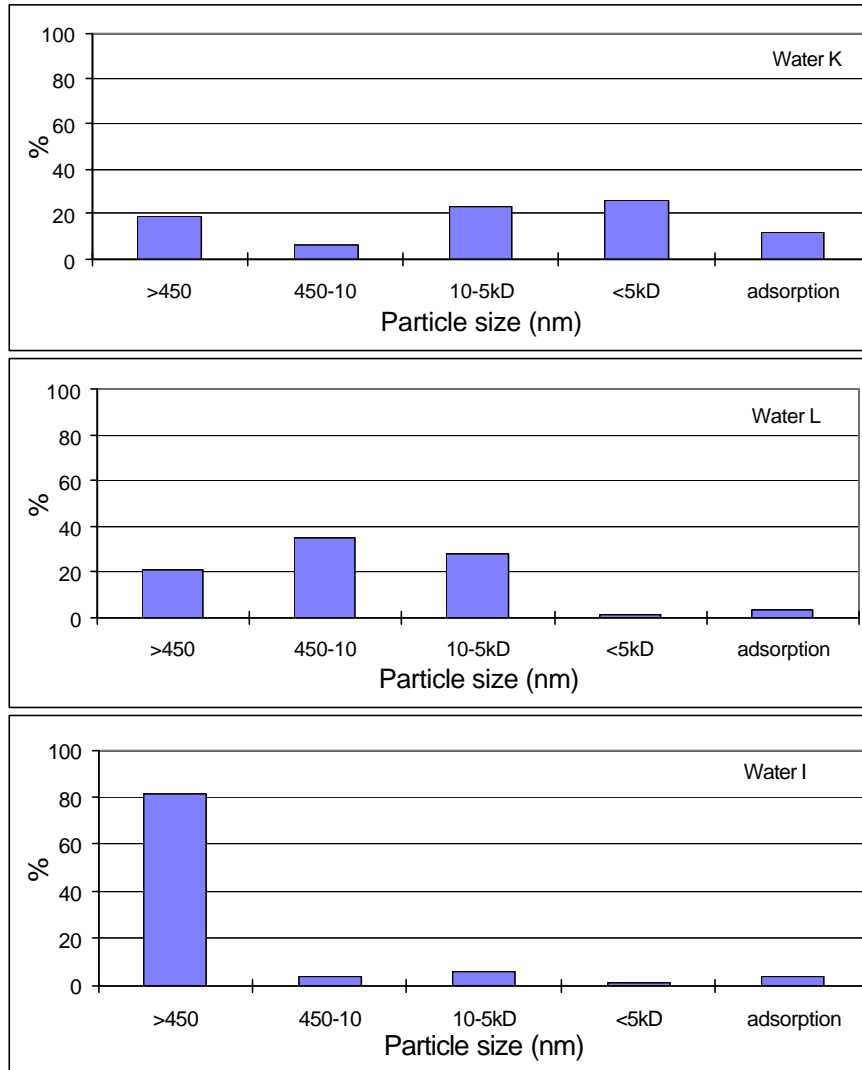


Figure 8. Percentage proportions of ^{210}Pb in the total activity bound in various particle size fractions from ground waters K, L and I.

One further objective of this study was to investigate the possible effect of the oxidation state of uranium on its speciation in ground water. The separation of the oxidation state U(IV) from the oxidation state U(VI) was carried out in two different ground waters. The ratio of the U(IV) form having a low solubility to the highly soluble U(VI) form and the radioactivity concentrations of the uranium isotopes ^{234}U and ^{238}U as well as the total uranium concentration were determined. The results of the uranium analyses are set out in Table XI.

Table XI. The concentrations of U(IV), U(VI) and total uranium as well as the radioactivity ratio of $^{234}\text{U}/^{238}\text{U}$ in unfiltered drilled well water samples. The statistical error (1d) of radioassay is indicated.

Sample	^{238}U (mBq/l)	^{238}U ($\mu\text{g/l}$)	$^{234}\text{U}/^{238}\text{U}$
Water K U _{tot}	500 ± 16	40.5 ± 1.3	1.71 ± 0.07
Water K U(IV)	10.5 ± 0.4	0.85 ± 0.04	1.83 ± 0.09
Water K U(VI)	312 ± 8	25.3 ± 0.6	1.63 ± 0.05
Water L U _{tot}	6720 ± 180	545 ± 15	1.28 ± 0.05
Water L U(IV)	179 ± 6	14.5 ± 0.5	1.27 ± 0.06
Water L U(VI)	6510 ± 180	528 ± 15	1.26 ± 0.05

The radioactivity ratio of U(IV) to U(VI) in the waters K and L were 0.034 and 0.027, respectively. Practically all uranium in both ground waters was in the highly soluble U(VI)- form. The ratio of $^{234}\text{U}/^{238}\text{U}$ is higher in water K than in water L. In both cases the ratio is >1. The solubility of ^{234}U from the rock to the ground water is higher than that of ^{238}U , which is due to the recoil energy formed by the radioactive decay of the ^{238}U isotope.

3.12 Disposal of Radioactive Wastes from Water Treatment Methods. Recommendations for the EC

When different kinds of treatment methods are used to remove natural radioactivity from drinking water, wastes containing natural radioactivity will be produced. The wastes are in liquid or solid form. Liquid wastes are produced when materials used to accumulate radioactivity are regenerated or backwashed. Solid wastes are formed in cases where regeneration or

backwashing are not used or cannot be used, and when the materials are taken out of service.

GAC filters emit gamma radiation when they are in service. The higher the radon concentration and the larger the water usage, the more intense the external gamma dose rate around the filter. Furthermore, GAC filters also accumulate lead (^{210}Pb). In addition to retaining radon, GAC filters to some extent also retain uranium, radium (^{226}Ra), lead and polonium (^{210}Po).

Depending on the Fe- or Mn-removal system, high amounts of radionuclides may be accumulated by the equipment. Backwashing or regeneration at regular intervals, however, enables a safe daily use of these units because then radionuclides are rinsed out of the fixed bed and drained into the sewer. The regeneration interval is in most cases frequent enough to prevent this technique from causing a problem of waste disposal.

In connection with ion exchangers different operation principles and exchange materials can be utilised. Organic ion exchangers (resins) can usually be regenerated. The properties of many inorganic exchangers (mineral based) cannot be restored by regeneration and therefore they must be discharged after the exhaustion.

The radioactive wastes produced by membrane techniques are not accumulated into fixed matrices. The concentrate containing radionuclides, is constantly drained into the sewer as the unit operates. The concentrations of radionuclides in concentrate, however, are low and therefore are not considered as radioactive waste.

The water treatment methods that potentially produce radioactive wastes were identified. The amounts of radioactive wastes produced by different techniques were assessed on the basis of the average water consumption habits and the estimated concentrations of the radionuclides that are removed (Table XII).

Table XII. The water treatment methods that potentially produce radioactive wastes and the estimated average amounts of the waste produced. The average was estimated for a family of three people consuming water 570 L/d (total consumption, POE) and 10 m³/a (food and drink, POU).

Technique	Specification	Type of waste	U (mg/kg)	²²⁶ Ra (Bq/g)	²¹⁰ Pb (Bq/g)	²¹⁰ Po (Bq/g)
GAC filtration	POE, carbon used for 3 a	solid	100	0.5–3	15–75	15–75
Ion exchange	POE, regeneration weekly	liquid	1–10	10–50	6–50	6–50
	POE, no regeneration, 1 a	solid	1000–5000	10–50	5–30	5–30
	POU, no regeneration, 1 a	solid	100–1500	1–5	0.2–2	0.2–2
Adsorptive techniques	Pour-through, 100 L	solid	100–1000	0.2–1	0.05–0.2	0.05–0.2
	POU or pour-through	solid	1–1000	0.2–50	0.05–50	0.05–50

A questionnaire was sent to all the Member Countries in order to gather information on the existing national regulations and guidelines on treatment and disposal of radioactive wastes produced by water treatment. The availability of national surveys on natural radioactivity in drinking water and estimates of population doses were also asked in the questionnaire (Table XIII). No answers were received from Belgium, Greece, the Netherlands and Portugal.

Regulations against a private person possessing material containing radioactivity have been issued in Austria and Sweden. In most countries solid wastes produced by water treatment can be disposed of at the municipal dumps and liquid wastes discharged into the sewer system. In some cases, however, this depends on the activity of the waste.

Table XIII. *The feedback from the questionnaire sent to all the Member States.*

Question 1 (Q1): *“Is there a nation-wide or partly nation-wide survey on natural radionuclides in drinking water made in your country?”*

Question 2 (Q2): *“Is there an estimate of the population dose due to natural radioactivity in drinking water made in your country?”*

State	Q1	Q2	Maximum permissible concentration					Other information about natural radioactivity in drinking water
			²²² Rn (Bq/L)	U (Bq/L)	²²⁶ Ra (Bq/L)	²¹⁰ Pb (Bq/L)	²¹⁰ Po (Bq/L)	
Austria	yes	yes	-	7.4	0.123	-	-	-
Denmark	yes	no	-	-	-	-	-	No regulations
Finland	yes	yes	300	20	3	0.5	3	²²⁸ Ra: 2 Bq/L, effective dose < 0.5 mSv/a
France	yes	yes	-	160 µg/L	1	-	0.1	³ H: 100 Bq/L
Germany	yes	yes	-	-	-	-	-	-
Ireland	yes	yes	-	-	-	-	-	No regulations
Italy	local surveys	no	-	-	-	-	-	No regulations
Luxembourg	under prep.	no	-	-	-	-	-	No regulations
Spain	yes	yes						Gross alpha 0.1 Bq/L, gross beta 1 Bq/L
Sweden	yes	yes	100	-	-	-	-	If ²²² Rn > 1000 Bq/L, unfit for consumption
U.K.	yes	yes	-	-	-	-	-	No regulations

4. MAIN ACHIEVEMENTS

4.1 Survey of Literature on Natural Radioactivity in Drinking Water and Treatment Methods in European Countries

The literature study presents the main hydrochemical processes which are responsible for the solution transport of natural radionuclides in water. The main areas for potentially elevated contents of natural radionuclides in European ground water are pointed out (Figure 9) and data about the contents in drinking, mineral, ground and surface waters of 17 European countries are presented.

Further, an extended literature overview on treatment methods suitable for removing natural radionuclides is given and results from pilot and full-scale studies are discussed. Finally, human health aspects are mentioned and nation-wide and internationally accepted regulations regarding natural radionuclides in drinking water are summarised.

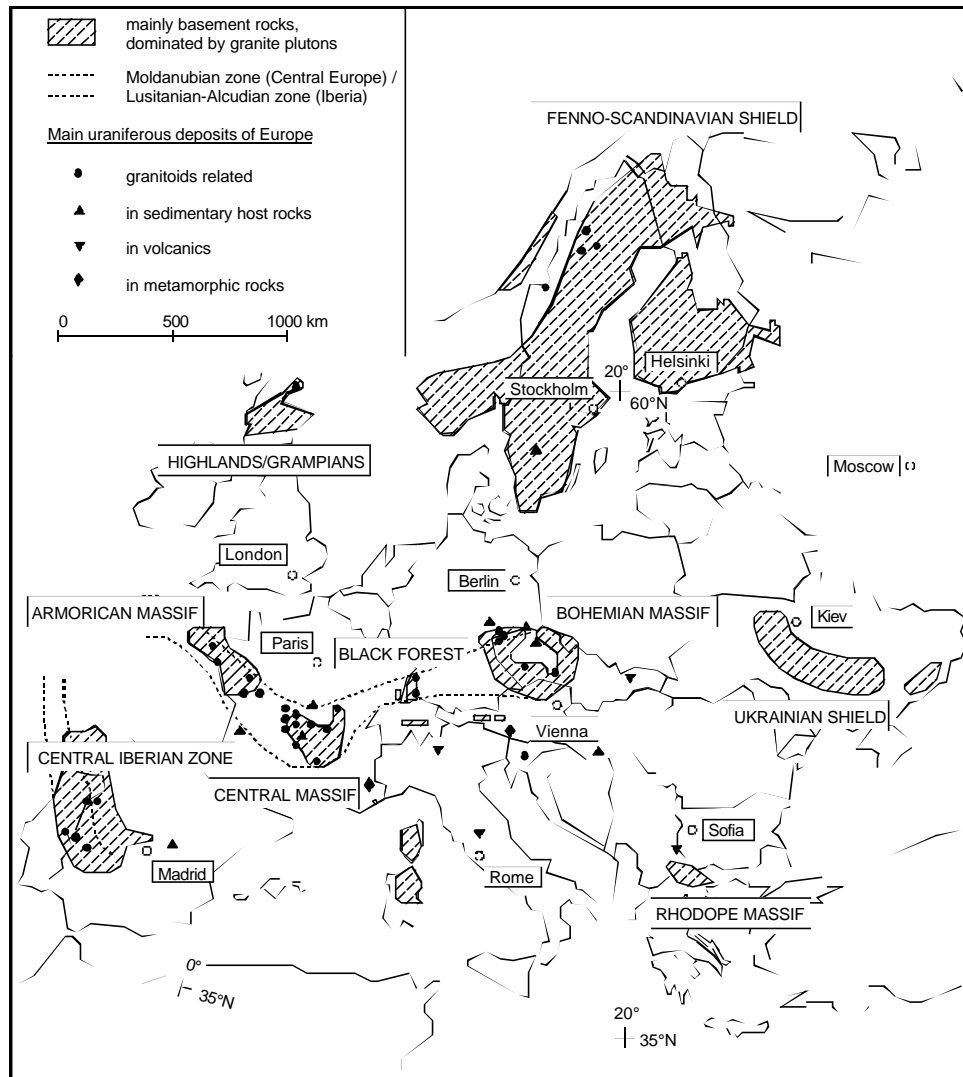


Figure 9. Main uraniumiferous deposits of Europe and zones dominated by basement rocks as areas with potentially elevated contents of natural radionuclides in ground water.

4.2 Intercomparison of Analysis Methods

The importance of having intercomparison exercises and proficiency tests accompanying the analytical work of the project is obvious from the

improvement in the quality of the data converging from exercise to exercise. For radon the problems encountered in the first intercomparison run were overcome in later intercomparison runs where the data reported by the participating laboratories were in excellent agreement.

For uranium and radium there was also a clear improvement in the consecutive intercomparison runs. Moreover, laboratories not specialised in the radium analysis of water samples on a routine basis had a chance to adapt their methods in order to improve the quality of their results. The improvement can be attributed to the information gathered from the intercomparison runs, the analytical experience acquired in the course of the project as well as the extensive discussions about measurement methods going on at the meetings.

4.3 Definition and Classification of Different Water Types and Experimental Conditions

Two internal TENAWA reports (“Definition of Water Types” and “Experimental Conditions”) were delivered; the content was accepted by all partners. The water types to be selected for tests as well as the experimental conditions were controlled using the reports delivered by the partners.

4.4 Removal of Radon by Aeration: Testing of Commercially Available Equipment for Domestic Use

The most efficient aerator in this study was “Radonett” manufactured by Sarholms Ab (4A). The removal rate of radon was also the best. “Radox” aerator made by Overcraft Oy (1A–1C) attained nearly as high an effective flow rate as “Radonett”. The removal efficiencies were also good. The RF series sold by Oy WatMan Ab (3A–3C) attained generally good removal efficiencies but the removal rate and the effective flow rate were low. “Orwa” made by Vartiainen Oy (2A–2C) attained both poor removal efficiencies and low effective flow rates.

During the study, the technical reliability of the aerators was monitored. Several technical failures occurred. The most important factors that must be considered when installing an aerator, were found to be

- the type and model of the aerator should be selected according to the water consumption and radon concentration
- radon concentration in raw water may vary and therefore the aeration time should always be set a couple of minutes longer than needed at the time of sampling
- the volume of the pressure tanks should be large enough to avoid shortage of water during peak consumption
- storage tanks or “dummy wells” were found to be a good solution to guarantee sufficient water supply
- by installing a small pressure tank before the aerator a better removal efficiency, shorter aeration time and a possibility of by-passing the system is attained
- a system by-pass is essential in most cases
- integration of the aerator to the other treatment units should be done so that one control unit regulates all the system components
- ion exchangers and iron and manganese removal equipment should be installed before the aerator
- if no other treatment is applied, a sediment filter should be placed before the aerator to protect the solenoid valves
- the room where the aerator is installed should be cool, dark and equipped with a floor drain. The building materials should be water-resistant. The air used for the aeration should be clean and the exhaust air ventilated outdoors efficiently. The outlet of the ventilation channel should be designed in such a way that no freezing or developing of mould can occur.
- an aerator should be equipped with an overflow pipe so that in case of malfunction no water damage can occur.
- the manufacturer should provide customers with an operation and maintenance manual. An unequivocal description of the installation (taps, by-pass valves, air filters, etc.) should also be provided. The manual should include a section “troubleshooting” in case something goes wrong.

Another important result of this study was the development of a standard testing protocol. Previously used conventional tests do not provide enough information either about the effective capacity of the aerators or about the real removal efficiency. With the new protocol developed the aerators can

be compared even-handedly. Also, malfunctions such as leaking solenoid valves can be detected.

A consumer guide was prepared. The guide is intended to be used by the water utility owner to enable one to define the problem and to evaluate the possible solutions in case the water contains excessive levels of natural radioactivity.

4.5 Removal of Radon by Aeration: Testing of Various Aeration Techniques for Small Waterworks

The study showed that only water aeration technology is able to produce extensive radon removal in waterworks. Other water treatment techniques were unable to remove more than 25% of radon. Venturi aeration equipment, installed in a German waterworks, removed from 70% to 80% of the water-dissolved radon. The disadvantage of Venturi aeration was that it causes high radon levels in the indoor air of the aeration room or reservoir.

Almost complete radon removal was achieved by shallow bed aeration. Additionally the process-air could be diverted without a greater effect on the radon content of the indoor air. At a packed tower column the process-air can also be diverted directly out of a waterworks building. The tested column in half-technical scale removed 85% of radon. At typical filling ring heights of two to three metres, as common in practical use, 95% can be expected.

Diffused bubble aeration combined with the spray aeration was efficient at removing radon in a new waterworks especially designed for the purpose. Diffused bubble aeration and spray aeration alike can be good alternatives to a packed tower aeration, especially in waterworks, where they can easily be combined with other existing water treatment processes. Water can be sprayed directly onto the filtration basins, which are needed in many treatment processes. Also, diffused bubble aeration can be easily applied in the existing basins. In such waterworks these two aeration methods are more economical than installing a packed tower aerator. The situation is the same when a packed tower is too high to be installed in an existing building.

Most of the various types of packed tower aerators removed radon very efficiently when installed in waterworks or tested in a pilot plant. Even

small units applied in a number of waterworks were efficient enough to supply water to dozens of households. Various types of commercial aerators originally designed for radon removal in domestic use can also be efficiently applied in small waterworks.

The results from waterworks which apply aeration in their iron or manganese removal processes, indicate that most of the radon was also removed. Aeration can be improved easily if better radon removal is acquired.

The experiments showed that already low air-to-water ratios of five cause high radon removal efficiencies and that carbon dioxide and radon show very similar removal behaviour. This was proved by the pilot plant tests as well as by the field measurements from waterworks.

The physico-chemical and microbiological water qualities at waterworks where measurements were carried out, remained good. The various water treatment processes rather improved the qualities when iron, manganese and carbon dioxide were removed.

A waterworks guide was prepared. The aim of the guide is to provide basic information on different aeration techniques, which can be applied for radon removal in small waterworks.

4.6 Removal of Radionuclides from Private Well Water with Granular Activated Carbon (GAC): Removal of Radon

The results of this study were mainly in good agreement with those obtained in studies in the USA over the last 20 years. Radon removal efficiency was very high (>99.9%) at many test locations. It seems that GAC filtration can be applied to mitigate unacceptably high concentrations of radon in ground waters that are most typically found in Finnish and Swedish bedrock. The water types studied were

- water that is soft and low in mineral content
- iron- and manganese-rich water (Fe 0.7 mg/L, Mn 0.26 mg/L)
- humus-rich water (TOC 3.4 mg/L) and
- slightly saline water.

It is possible that high concentrations of uranium, and possibly organic matter, lower the adsorption rate of radon. Uranium, as a toxic heavy metal, is harmful to human health and therefore high concentrations (>0.1 mg/L) should always be removed from drinking water. The combination of an anion exchanger installed before a GAC filter, worked well and was capable of removing both uranium and radon efficiently. High concentration of iron and manganese and the sediment filters installed before a GAC unit had no effect on the performance of the GAC filters. The GAC units were technically reliable. No loss of hydraulic pressure or water leakage was reported.

The intensity of gamma radiation originating from GAC units in permanent use was high. With the proper shielding, instructions and placement of the unit, elevated doses to the residents can, however, be avoided. The water quality at the test locations remained good.

A consumer guide was prepared. The guide is intended to be used by the water utility owner to enable one to define the problem and to evaluate the possible solutions in case the water contains excessive levels of natural radioactivity.