

raw water is very important in this context. The combined effects of the environment of the installation, for instance indoors in a warm cellar, the material of the equipment, for instance transparent or semi-transparent plastic, the technical design of the system, the quality of the air that is mixed with the water and the quality of the raw water. All these are factors that affect the hygienic quality of the water treated. More research is needed to investigate the risks involved.

## **5.5 Removal of Radon by Aeration: Testing of Various Aeration Techniques for Small Water Works**

The investigations showed that aeration is a highly effective method for removing radon from water. Removal efficiencies of more than 98% can be achieved, for example, with a fine bubble shallow bed aerator. Various types of aeration equipment are manufactured. All of them benefit from the same physical principle: gas exchange takes place at the interface of the phases of air and water. Therefore, each aeration method intends to create as large an interface as possible. The usability of a certain type of aeration equipment for removing radon, as well as CO<sub>2</sub>, is very much dependent on several operation parameters, especially the amount of water to be treated, the available space and the degassing target. Most aeration facilities can be constructed to achieve radon removal efficiencies of more than 95% or even more than 99%. In most modern aeration facilities, where an active use of air takes place, high gas exchange rates are mainly a question of the throughput of air, which means a question of operation costs.

It was further recognised that radon and carbon dioxide show a very similar removing behaviour during aeration, which can be explained by the similar Henry's law constants for both gases (radon:  $2.26 \cdot 10^3$  bar and CO<sub>2</sub>:  $1.51 \cdot 10^3$  bar; at 20°C water temperature and atmospheric pressure). Therefore, it is possible to estimate the radon removal efficiency of aeration equipment from its carbon dioxide removal efficiency. The latter has to be known by the manufacturer, since water aeration is a widespread treatment method for the de-acidification of water.

Finally, the study showed that water aeration is a very effective tool for radiation protection in waterworks. By operating water aeration equipment it is possible to reduce the radon degassing potential (from the treated

water into the air) to a minimum and to reach moderate indoor air radon levels. To achieve this, it is necessary though that the process-air is led out of the aeration equipment and out of the waterworks completely.

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

GAC filtration can be considered an inexpensive and easy way of mitigating high concentrations of radon in household water.

The longevity of a GAC batch was not discovered, because most filters exhibited constant removal efficiency for radon throughout the study. Therefore, no recommendations regarding the effective lifetime of a GAC batch can be given.

It was obvious that some anionic species reduced the adsorption rate of radon on GAC. According to the results, this could be either humus or uranium. The data, however, were too limited. At present there are some 50 GAC filters installed for radon removal in Finland. In order to give recommendations concerning the maximum levels of the interfering substances more water quality data are needed from these filters.

One of the main concerns in applying GAC filtration in domestic use is the external gamma radiation that can cause radiation exposure for the residents. An external dose rate as measured on the surface of a GAC unit installed in permanent use could exceed the normal background level even by a factor of one thousand. With proper shielding, instructions and placement of the unit in a non-residential area, elevated doses to the residents, however, can be avoided.

In order to minimise exposures different types of radiation shields have been studied. Lead attenuates gamma radiation most efficiently. A lead shield, however, may be expensive and it is made of toxic metal, which must be considered a potential health risk. Bricks and concrete can be applied, but the thickness of the shield must be considerably greater than for lead. A water jacket can be built. Water attenuates gamma rays, and is cheap. However, residential radiation exposure cannot always be eliminated sufficiently, especially when the influent radon activity is high. Therefore

radon removal applying GAC filtration often remains a viable treatment method only when the radon concentration is low.

## **5.7 Removal of Radionuclides from Private Well Water with Granular Activated Carbon (GAC): Removal of U, Ra, Pb and Po**

When considering removal of uranium, radium ( $^{226}\text{Ra}$ ), lead ( $^{210}\text{Pb}$ ) and polonium ( $^{210}\text{Po}$ ) with activated carbon the type of carbon should be selected based on its adsorptive properties for these radionuclides. Activated carbons exhibit high non-polar capacities for hydrophobic substances such as radon and many organic contaminants. However, their polar properties are usually very limited. Therefore they remove inorganic substances and cations, such as heavy metals, only fairly well. A possible solution for the simultaneous removal of radon and the long-lived radionuclides could be the carbon-mineral adsorbents. The matrices of these adsorbents consist of both active carbon and mineral adsorbents ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , etc.) and show good mechanical properties. Furthermore, these adsorbents usually have better adsorptive properties than each individual component separately.

The mean removal efficiency of uranium, radium, lead and polonium in the field experiments is generally not as good as in the laboratory experiments. In the field tests the removal of uranium and radium decreased gradually with the amount of water treated and the removal of radium was a little higher than that of uranium. The results of polonium and lead from the laboratory and field tests agree much better than for uranium and radium. The reasons to the observed differences have not been fully analysed, but they can be explained partly by the amount of water treated and also by the chemical speciation, which may have the greatest effect.

During the TENAWA project speciation studies were carried out. The differences between the laboratory and field experiments in this study can be explained to some extent by the results from these speciation studies. During these studies filtration experiments were made to find out if uranium, radium, lead or polonium occur in ground waters either as ionic compounds or bound to various sizes of particles.

The results indicated that uranium and radium occur mainly as ions. Because lead and polonium were mainly bound to particles they can be removed from water by utilising adsorption into GAC filters. Correspondingly, uranium and radium should be removed predominately by ion exchangers. These observations are in good agreement with the results obtained by ion exchange experiments carried out during the TENAWA project. It should also be noted that the Finnish ground waters are still softer than any model water used in the lab tests.

However, the variation of the adsorption values obtained in the field experiments indicate that GAC filtration is not very suitable for the adsorption of natural radionuclides, except radon, which is retained as a noble gas very efficiently, even after large volumes of filtered water.

## **5.8 Removal of Radioactivity by Methods Used for Fe- and Mn-removal from Private Wells**

There are still a few questions that remained unanswered. The physico-chemical conditions during the filtration should be examined in greater detail. For example, the aeration-filtration equipment contain various types of masses which have different retention properties. Therefore, the accurate composition of the masses added in the filtration layers need to be known in order to evaluate the results more reliably. At some test locations sampling needs to be continued to discover why the change of masses affected the removal rates.

Also the reduction of lead and polonium varied in a large range. The reason is not know exactly but it may be due to the speciation. Recent studies performed in Finland have indicated that lead and polonium occur in waters mainly adsorbed to various sizes of particles and not so much as soluble compounds. Thus lead and polonium would preferentially be removed by methods used for removing particles rather than by ion exchange.

## **5.9 Removal of U and Po from Private Ground Water Wells Using Anion Exchange Resins and Removal of Ra and Pb from Private Ground Water Wells Using Cation Exchange Resins**

Ion exchange is a proper method for the removal of radium and uranium. Strong basic anion resins for the removal of uranium and strong acidic cation resins for radium removal performed best. The efficiency for lead and polonium varies a great deal, since most of these nuclides are supposed to be particle bound in natural waters and therefore no ion exchange process in the real sense but adsorption to the resins is responsible for their reduction. Therefore the reduction of lead and polonium is a welcome side-effect of uranium and radium removal but ion exchange is not the technology of choice for their removal.

The main disadvantage of cation exchange resins in the sodium form is the more or less total removal of hardness simultaneously with radium. This can be avoided by using resins in the calcium form. For the application of the regenerant  $\text{CaCl}_2$  in commercially available systems changes in design are necessary. Other influences on water quality which were observed are a decrease in turbidity, phosphate, sulphate and nitrate with anion resins and a reduction in iron mainly with cationic resins. The pH value and the concentration of competing ions had an important influence on the possible run-length of the ion exchangers and must be considered when fixing the period of time between two regeneration procedures. Hygienic deterioration of the water was detected in some cases and cannot be excluded.

No remarkable dose to the residents caused by the treatment systems was observed when the equipment was properly located in the house. But national regulations regarding the handling of waste and the permitted accumulation of radioactivity on the filters may limit the applicability of this technology for private homes.

## **5.10 Removal of U, Ra, Pb and Po with Adsorptive or Membrane Filters.**

By RO and NF systems liquid waste—the retentate—is produced. Due to the fact that no additional chemicals are necessary, the retentate is merely

a more concentrated form of the raw water. Concerning radioactivity the mixing of treated water (used in households, low radioactivity) and retentate (high radioactivity) should in sum result in household waste water with the original natural radionuclide concentration.

Because of the increased raw water volume necessary for producing drinking water, membrane technology—if in widespread use—could become a problem in the case of limited water resources and for the capacity of waste water treatment plants if retentate is not alternatively used (e.g. for flushing the toilet).

The experiments showed that part of the removed radionuclides is adsorbed in the treatment units. Depending on national legislation used filter cartridges or membranes have to be handled as ordinary household waste or as low radioactive waste. As a result this can be a key economic question for the use of such treatment devices.

The installation and maintenance of POU systems should be possible without special skills whereas with POE systems this should be done by professionals. The regular use of the units is important because otherwise the membranes would be destroyed.

The reduction of water constituents can be a disadvantage for the consumer of drinking water which is treated by RO, because it is not advisable to drink water which is almost completely de-mineralised. After treatment it would be preferable to have slight water re-hardening.

In natural water the uranyl carbonate complexes  $\text{UO}_2\text{CO}_3^0$ ,  $\text{UO}_2(\text{CO}_3)_2^{2-}$ ,  $\text{UO}_2(\text{CO}_3)_3^{4-}$  and, if phosphate is present, the uranyl phosphate complex  $\text{UO}_2(\text{HPO}_4)_2^{2-}$  are mainly responsible for the mobility of uranium. Below pH 5, the pure uranyl cation  $\text{UO}_2^{2+}$  is also important. Those five uranium species have been generated in model waters and their rejection at six NF membranes and two open RO membranes was determined in several experiments.

The results show that the uranium removal from water at the six tested NF membranes was mainly between 90% and 98%. Especially the three divalent and multivalent uranyl anion complexes  $\text{UO}_2(\text{HPO}_4)_2^{2-}$ ,  $\text{UO}_2(\text{CO}_3)_2^{2-}$  and  $\text{UO}_2(\text{CO}_3)_3^{4-}$  were mostly removed up to 95% or more. Those three complexes are the predominant uranium species in natural water above pH 4. The uncharged uranyl carbonate complex,  $\text{UO}_2\text{CO}_3^0$ , that predominates in

phosphate-free water between pH 5 and 6.5, was also removed to about 95% in most cases. Besides, the rejection of the pure uranyl cation at pH 3.2 was from 87% to 93%. The high rejection of these five uranium compounds is a first sign that uranium can be removed quite effectively from water by NF membranes. This seems to be valid over a wide range of hydrochemical settings, even in very acidic waters.

The experiments with the extraordinary high uranium concentration of 10 mg/L showed no major difference in the removal efficiencies of the membranes, compared to the 1 mg/L experiments. Therefore, clearly worse removal efficiencies are not to be expected during concentration processes at membranes, which will take place in the case of a higher recovery. Further, there seems to be no clear effect on the uranium removal efficiency due to the presence of a high number of competing ions in the water. This was shown by the experiments with high and low sulphate concentrations.

The rejection results of the three NF membranes (out of 6) studied showed quite similar results: uranium rejection from 95% to 98% and rejection of other water constituents (phosphate, bicarbonate and electrical conductivity) from 75% to 97%. One membrane rejected uranium slightly worse (from 91% to 97%) and other water constituents slightly better (from 80% to 98%). One membrane also removed uranium effectively (from 95% to 98%), but the rejection of other water constituents was only from 45% to 95%. One of the membranes studied had a uranium rejection from 81% to 98% and the rejection of other water constituents from 40% to 80%.

Beside the six NF membranes two RO membranes were tested for comparison. As was expected, these membranes rejected both uranium (from 98% to 99.5% at pH 5 to 8.3) and other water constituents (from 93% to 99.5%) more effectively than the NF membranes.

Finally, the amount of organic uranium species can be estimated, since several authors assume that a certain part of uranium mobilised in water might be due to organic compounds. It can be estimated that the rejection of organic uranium compounds would not be lower than the rejection of the compounds investigated. The reason is that any organic uranyl species, whether anionic, cationic or uncharged, would surely be bigger and heavier than the inorganic uranyl compounds investigated. The molecular weight of the compounds investigated, however, was the main factor for the quite high rejection at all membranes. This is indicated by the similarity of the results of the uranium removal efficiencies in all experiments, without depending

on the charge of the compounds. And indeed, even the molecular weight of the lightest uranium compound, the pure uranyl cation,  $\text{UO}_2^{2+}$  (270 Dalton), is already above the typical molecular weight cut-off (MWC: weight of uncharged organic molecules which are rejected practically completely) of NF membranes. The molecular weight of  $\text{UO}_2(\text{HPO}_4)_2^{2-}$ , for example, is 460 Dalton. The typical MWC of NF membranes is about 250 Dalton.

## 5.11 Speciation of U, Ra, Pb and Po in Water

The removal of uranium, radium, lead and polonium from drinking water depends on their speciation. The speciation of radionuclides in drinking water requires information as to their physico-chemical form in the water phase. For removal of these nuclides knowledge of their speciation in ground water is necessary. It is important to know in which physico-chemical form the radionuclide exists in ground water and how different factors affect its speciation.

Under oxidising conditions uranium exists mainly as its hexavalent state while in reducing condition U(IV) is the predominant oxidation state. U(VI) is present in slightly acid ground waters mainly as  $\text{UO}_2^{2+}$ . It forms strong complexes with carbonate and hydroxide ions. Uranyl ion is also known to form stable complexes with dissolved organic matter, in the form of humic and fulvic acid. Uranium can also form strong complexes with phosphate, fluoride and sulphate, when these anions are present.

Radium is most frequently found as hydrated  $\text{Ra}^{2+}$  cation but it can also form complexes with sulphate anions. Radium forms complexes with chloride ions in saline waters. Radium is readily removed from the solution by coprecipitation with insoluble sulphates. Salinity affects the concentration of radium because a solution containing high concentration of cations can exchange radium from a solid phase into the solution.

Lead is particle reactive. It hydrolyses strongly and is adsorbed by minerals. Lead forms many slightly soluble compounds, such as basic lead carbonate and lead silicate. Lead exists in ground water mainly in colloids and coarse particles. In saline ground water Pb forms a soluble lead chloride complex.

Polonium is also particle reactive and it hydrolyses easily. The hydroxy-species can easily be associated with colloids and active surfaces. Organic

matter can affect the speciation of polonium. It has been observed that in oceans polonium is adsorbed by organic particles and is enriched in the microlayer of the ocean surfaces. It has also been noticed that bacteria can increase Po concentration in ground water.

The experimental work on the speciation of polonium and lead in ground water indicated that for reliable results it was necessary to use natural ground water as sample material. Using tracers instead of determining naturally occurring polonium and lead can lead to completely false results. The results regarding the proportions of  $^{210}\text{Po}$  and  $^{210}\text{Pb}$  bound in various particle fractions in ground water have helped other partners to interpret the results obtained by developing different removal methods of natural radionuclides used in the present project.

In the ground waters from drilled wells studied practically all uranium was in highly soluble U (VI) form. Thus, it can be assumed that the oxidation states of uranium has no significant role in removing uranium from drinking water. Instead the pH of ground water affects the removal of uranium and should be studied in more detail in future.

## **5.12 Disposal of Radioactive Wastes from Water Treatment Methods: Recommendations for the EC**

It was pointed out that the radioactive wastes which arise from the treatment of water involve natural radionuclides, but their production, processing, handling, use, holding, etc. cannot be considered practice (as stated in the Basic Safety Standard) and the exemption levels of the Basic Safety Standards are not applicable. That is why there is the possibility of adopting a totally new approach when considering the attitude towards the radioactivity and waste containing natural radioactivity-related problems in connection with different methods for removing radioactivity from drinking water.

It was proposed to recommend that the annual dose to inhabitants from external gamma radiation of GAC filter should not exceed 0.1 mSv. When methods for removing natural radioactivity from drinking water are applied, normally the doses which need to be avoided are of the order of 1 mSv per year. This is why a removal method which simultaneously acts as a gamma

radiation source and might irradiate dwellers can not be allowed to cause doses of the same order. The limit should be much smaller—one tenth—otherwise the whole procedure does not make sense. On the other hand, doses much smaller cannot be considered, because the doses from natural radioactivity normally encountered are quite high. In Finland doses from inhalation of radon are about 1–2 mSv per year and from gamma radiation of building materials about 0.1 mSv per year.

It was also proposed to recommend that the dose rate at a distance of 1 m from the GAC filter should not exceed 1  $\mu$ Sv/h. This limit means that one should stay close to the source 100 hours per year, to receive the 0.1 mSv dose presented in the previous chapter. Normally this equipment is located in such parts of the dwellings that longer stays are not needed.

It was also proposed to recommend that possible solid and liquid wastes associated with removal methods could be delivered to communal dumps or discharged into the sewer. The procedures with the radioactive wastes should be as simple as possible to deal with. This encourages private citizens to start using some radioactivity removal method in connection with their own water supplies, if needed. If too complicated procedures are applied the dwellers keep on drinking the water containing high amounts of natural radioactivity.

The private companies selling removal equipment do not want to have responsibility for the possible wastes. Many times the company selling the equipment has nothing to do with the fitting of the equipment at its place of use. The fitters are locally operating private plumbers or small companies.

The fear of radioactivity operates in both directions. People are afraid of radioactivity and want to decrease the amount of natural radioactivity in their drinking water. On the other hand, when this is done there is a special problem with the wastes containing radioactivity. Difficulties in getting rid of them or expensiveness of this process may oppose the idea of lowering concentrations in drinking water.

## **6. PUBLICATIONS RELATED TO THE PROJECT**

### **6.1 Publications**

Haberer K, Raff O, Akkermann-Kubillus A. Natural Radionuclides in Drinking Water in Europe and Treatment Methods for their Removal. Oxford: Elsevier Science, (in press).

Huikuri P, Salonen L, Raff O. Removal of Natural Radionuclides from Drinking Water by POU Reverse Osmosis. *Desalination* 1998; 3, 119: 235–239.

Raff O, Haberer K, Wilken R-D, Stauder S. Radon-Entfernung in Wasserwerken mit hoher Radonbelastung. In: *Radioaktivität in Mensch und Umwelt. Band 1 der Jahrestagung des Fachverband Strahlenschutz*, 28.9.–2.10.98, Lindau. Köln: TÜV-Verlag GmbH, 1998.

Haberer K, Akkermann-Kubillus A, Dalheimer A. Verhalten von natürlichen Radionukliden in Aktivkohlefiltern. In: *Radioaktivität in Mensch und Umwelt, Band 1 der Jahrestagung des Fachverband Strahlenschutz*, 28.9.–2.10.98, Lindau. Köln: TÜV-Verlag GmbH, 1998.

Raff O, Wilken R-D. Removal of Dissolved Uranium by Nanofiltration. In: *Proceedings of the workshop: Desalination Technologies for Small and Medium Size Plants with Limited Environmental Impact. December 3.–4.1998, Rome (accepted by Desalination, 1999).*

Raff O, Funk H, Wilken R-D. Reduction of Indoor Air Radon Contents in German Waterworks by Removal of Radon from Water by Aeration. In: *Proceedings of the Workshop: Radon in the Living Environment. 19–23 April 1999, Athens (submitted to Sci.tot.environ).*

Raff O, Wilken R-D. Uranentfernung aus Trinkwasser durch Nanofiltration. In: *Tagungsband des 7. Aachener Membran Kolloquiums. 9.–11.3. 1999. Aachen: Verlag Mainz, 1999: 253–256.*

Haberer K. Radium-226 in Filterschlammern der Grundwasseraufbereitung. Vom Wasser 1999; 92: 335–345.

Raff O, Wilken R-D. Uranium removal from water by nanofiltration. Mine Water and the Environment. Proceedings of the Conference of the International Mine Water Association: Mine, Water & Environment for the 21<sup>st</sup> Century, Sevilla, September 13–17 1999; 1: 321–324.

Huikuri P, Salonen L. Removal of uranium from Finnish groundwaters in domestic use with a strong base anion resin. To be published in J.Radioanal.Nucl.Chem. 2000; 243, 2.

Turtiainen T, Salonen L, Myllymäki P. Radon removal from different types of groundwater applying granular activated carbon (GAC) filtration. To be published in J.Radioanal.Nucl.Chem. 2000; 243, 2.

Raff O, Haberer K. Radon-222 in Ground Water in the German Rhine-Nahe-Area. Vom Wasser 1998; 90: 311–317.

Raff O, Funk H, Wilken R-D. Maßnahmen zur Radonreduzierung in Wasserwerken. In: Forschung zum Problemkreis "Radon". Vortragsmanuskripte des 12. Statusgespräches vom 26., 27. October 1999. Bundesministerium für Umwelt, Natrschutz u. Reaktorsicherheit, Berlin 1999.

Haberer K, Raff O. Removal of Naturally Occurring Radionuclides from Drinking Water—An Overview. Submitted to Vom Wasser, September 1999.

Salonen L, Huikuri P, Turtiainen T. Luonnon radioaktiiviset aineet pohjavesissä – poistolaitteiden tarve ja kehittäminen Suomessa. Vesitalous 1998; 4: 35–40.

Myllymäki P, Salonen L, Turtiainen T. Radon and uranium removal from bedrock water in Finland. In: Proceedings of the 2nd International Conference on Future Groundwater Resources at Risk, Changchun, China, 14.–16.7.1998. UNESCO, Waterway.

Huikuri P, Turtiainen T. Radon voidaan poistaa juomavedestä. ALARA 1998; 2: 6.

Salonen L. Suomessa on kehitetty laitteita radioaktiivisuuden poistoon porakaivovesistä. *Ympäristötekniikka* 1999; 4: 12–13.

Lehto J, Kelokaski P, Vaaramaa K, Jaakkola T. Soluble and Particle-Bound  $^{210}\text{Po}$  and  $^{210}\text{Pb}$  in Groundwaters. *Radiochim. Acta* 1999; 85: 149–155.

## 6.2 Poster presentations

Raff O, Akkermann-Kubillus A, Haberer K, Wilken R-D. Radon Removal by Common Water Treatment. In *Symposium: New aspects of radiation measurements, dosimetry and alphaspectrometry*. March 4–6, 1998, Dresden.

Raff O, Akkermann-Kubillus A, Haberer K, Wilken R-D. Natürliche Radionuklide in Wasserwerken. In: *DVGW/BGW Wasserfachliche Aussprachtagung*, 3.–4.3.1998, Bremen.

Vaaramaa K, Lehto J, Jaakkola T. Removal of Natural Radionuclides from Potable Water by Ion Exchange. In the *13th Radiochemical Conference*, April 19th–24<sup>th</sup> 1998, Czech Republic.

Huikuri P, Salonen L, Raff O. Removal of Natural Radionuclides from Drinking Water by POU Reverse Osmosis. In: *Membranes in Drinking and Industrial Water Production*, September 21–24, 1998, Amsterdam.

## 6.3 Abstracts

Salonen L, Turtiainen T, Huikuri P. Application of liquid scintillation spectrometry for testing filter material capabilities to remove radon daughters from drinking water. In: *the 7th International Conference on Low-Level Measurements of Actinides and Long-Lived Radionuclides in Biological and Environmental Samples*, Salt Lake City, USA, September 21–25, 1998.

## 6.4 Technical Deliverables

Haberer K, Raff O, Akkermann-Kubillus A, Wilken R-D. Natural Radionuclides in Drinking Water in Europe and Treatment Methods for their Removal. WP 1.1 Literature Study Report.

Schönhofer F. General Considerations: Intercomparison of Analytical Methods. WP 1.2 Preliminary Report.

Kralik C. General Considerations: Intercomparison of Analytical Methods. WP 1.2 Final Report.

Weingartner A, Staubmann K. General Considerations: Experimental Conditions. WP 1.3 Interim Report.

Weingartner A, Staubmann K. General Considerations: Definition and Classification of Different Water Types. WP 1.3 Interim Report.

Mjönes L. Radon Removal Equipment Based on Aeration: A Literature Study of Tests Performed in Sweden between 1981 and 1996. WP 2.1 Literature Study Report.

Turtiainen T, Mjönes L. Removal of Radon by Aeration: Testing of Commercially Available Equipment for Domestic Use. WP 2.1 Preliminary Report.

Turtiainen T, Mjönes L, Salonen L. Removal of Radon by Aeration: Testing of Commercially Available Equipment for Domestic Use. WP 2.1 Final Report.

Salonen L. Removal of Radon by Aeration: Testing of Various Aeration Techniques for Small Waterworks. WP 2.2 Aeration Systems Designed.

Salonen L. Removal of Radon by Aeration: Testing of Various Aeration Techniques for Small Waterworks. WP 2.2 Preliminary Report.

Salonen L, Turunen H, Mehtonen J, Mjönes L, Hagberg N, Wilken R-D, Raff O. Removal of Radon by Aeration: Testing of Various Aeration Techniques for Small Water Works. WP 2.2 Final Report.

Salonen L, Turtiainen T, Turunen H, Raff O, Wilken R-D, Hagberg N. Waterworks Guide (WP 2.2).