STUK-A193 / DECEMBER 2002

REMOVAL OF RADON BY AERATION: TESTING OF VARIOUS AERATION TECHNIQUES FOR SMALL WATER WORKS

For European Commission
under Contract No FI4PCT960054
TENAWA project

L. Salonen[1)], H. Turunen[2)], J. Mehtonen[1)],
L. Mjönes[3)], N. Hagberg[3)], R-D. Wilken[4)], O. Raff[4)]

[1)] STUK–Radiation and Nuclear Safety Authority, Finland
[2)] Vartiainen Oy, Water Engineering Company, Finland
[3)] SSI, Swedish Radiation Protection Institute, Sweden
[4)] ESWE, Institute of Water Research and Water Technology, Germany

STUK • **SÄTEILYTURVAKESKUS**
STRÅLSÄKERHETSCENTRALEN
RADIATION AND NUCLEAR SAFETY AUTHORITY

Osoite/Address • Laippatie 4, 00880 Helsinki
Postiosoite / Postal address • PL / P.O.Box 14, FIN-00881 Helsinki, FINLAND
Puh./Tel. +358 9 759 881 • Fax +358 9 759 88 500 • www.stuk.fi

The conclusions presented in the STUK report series are those of the authors and do not necessarily represent the official position of STUK

ISBN 951-712- 629-8(print)
ISBN 951-712- 630-1(pdf)
ISSN 0781-1705

Dark Oy,Vantaa/Finland, 2002

Sold by:
STUK – Radiation and Nuclear Safety Authority
P.O. Box 14, FIN-00881 Helsinki, Finland
Phone: +358 9 759881
Fax: +358 9 75988500

SALONEN Laina, TURUNEN Hannu, MEHTONEN Jukka, MJÖNÄS Lars, HAGBERG Nils, WILKEN Rolf-Dieter, RAFF Oliver. STUK-A193. Removal of radon by aeration: Testing of various aeration techniques for small water works. Dark Oy 2002, 44 pp.

Keywords radon, uranium, radon removal, uranium removal, water aeration, diffused bubble aeration , packed tower aeration, spray aeration, Venturi aeration, anion exchanger, groundwater

Abstract

Capability of various aeration techniques to remove radon from water in small waterworks was studied as a part of project (Treatment Techniques for Removing Natural Radionuclides from Drinking Water), which was carried out during 1997–1999 on a cost-shared basis (contract No. F14PCT960054) with The European Commission (CEC) under the supervision of the Directorate-General XII Radiation Protection Research Unit.

In TENAWA project both laboratory and field experiments were performed in order to find reliable methods and equipment for removing natural radionuclides from ground water originating either from private wells or small waterworks. Because such techniques are more often needed in private households than at waterworks, the main emphasis of the research was aimed to solve the water treatment problems related to the private water supplies, especially bedrock wells. Radon was the most important radionuclide to be removed from water at waterworks whereas the removal of other radionuclides (^{234,238}U, ^{226,228}Ra, ^{210}Pb and ^{210}Po) was often required from radon-rich bedrock waters. The currently available methods and equipment were mainly tested during the field and laboratory experiments but the project was also aimed to find new materials, absorbents and membranes applicable for radionuclide removal from various types of ground waters (e.g. soft, hard, acidic). Because iron, manganese or organic occur in waters with radionuclides, their simultaneous removal was also studied. The project was divided into 13 work packages. In this report the results of the work package 2.2 are described.

Elevated levels of radon and other natural radionuclides in European ground waters have been observed mainly in wide areas of the crystalline Scandinavian bedrock, especially in the granite rock areas of Finland and Sweden but also in more limited crystalline rock areas of Central and Southern

Europe, Ukraine and Scotland. The radon removal efficiencies of different aeration methods (diffused bubble, packed tower and spray nozzle aeration) and commercial aerators were studied in a number of Finnish, Swedish and German waterworks. Part of the aeration systems applied in the waterworks was originally designed for radon removal and the rest for removing Fe, Mn, CO_2 or H_2S. Radon concentration in raw waters varied between 8 – 5 800 Bq/l.

Diffused bubble aeration combined with spray aeration removed 98% of radon in one waterworks especially designed for radon removal. Very efficient radon removals (88 – 99%) were achieved in most waterworks using packed tower aeration whereas radon reduction using spray nozzle aeration varied in a larger range (67 – 98%). The efficiency of spray nozzle aeration can be improved easily in most plants if necessary. Various types of commercial aerators, although designed originally for radon removal in domestic use, can be applied efficiently (67 – 99%) also in small waterworks. The radon removals varied in large range (13 – 98%) in waterworks using aeration for removing Fe, Mn, CO_2 or H_2S. Quite similar radon (about 85%) and CO_2 (about 75%) removals were achieved as a packed tower column was tested in pilot plant experiments. This agreed with the results obtained from different waterworks studied here. Practically all uranium (99.9%) was removed from water in one waterworks when a strong base anion exchanger was used.

SALONEN Laina, TURUNEN Hannu, MEHTONEN Jukka, MJÖNÄS Lars, HAGBERG Nils, WILKEN Rolf-Dieter, RAFF Oliver. STUK-A193. Radonin poisto ilmastamalla: Eri ilmastusmenetelmien testaaminen pienten vesilaitosten käyttöön. Dark Oy 2002, 44 s. Englanninkielinen.

Avainsanat radon, uraani, radonin poisto, uraanin poisto, veden ilmastus, hienokuplailmastus, torni-ilmastus, suihkutusilmastus, Venturi-ilmastus, anioninvaihdin, pohjavesi

Tiivistelmä

Eri ilmastusmenetelmien kykyä poistaa radonia pienten vesilaitosten vedestä tukittiin osana TENAWA (Treatment Techniques for Removing Natural Radionuclides from Drinking Water) projektia (sopimus Nro. F14PCT960054). Projekti toteutettiin vuosina 1997 ja 1999 yhteisrahoitteisesti Euroopan Komission kanssa ja sen valvojana toimi pääosasto XII:n Radiation Protection Research Unit.

TENAWA projektissa tehtiin sekä laboratorio- että kenttäkokeita, jotta löydettäisiin luotettavasti toimivia poistomenetelmiä ja laitteita luonnon radionuklidien poistamiseksi yksityisten kaivojen ja pienten vesilaitosten vesistä. Koska tällaista tekniikkaa tarvitaan huomattavasti useammin yksityistalouksissa kuin vesilaitoksilla, tutkimuksen pääpaino suuntautui yksityisten vesilähteiden, erityisesti porakaivojen, vedenkäsittelyongelmien ratkaisemiseen. Vesilaitosten vesistä poistettavista radioaktiivista aineista radon on tärkein, kun taas radonpitoisista porakaivovesistä joudutaan usein poistamaan myös muita radioaktiivisia aineita (^{234,238}U, ^{226,228}Ra, ^{210}Pb and ^{210}Po). Laboratorio ja kenttäkokeet painottuivat pääasiassa nykyisten menetelmien ja saatavilla olevien laitteiden testaamiseen, mutta projektin tavoitteena oli myös löytää uusia materiaaleja, adsorboivia aineita ja kalvoja, jotka kykenisivät poistamaan radionuklideja erityyppisistä pohjavesistä (esim. pehmeistä, kovista, happamista). Koska pohjavesissä esiintyy radionuklidien ohella usein myös rautaa, mangaania ja orgaanista ainetta, myös niiden samanaikaista poistoa tutkittiin. Projekti jakautui 13 työpakettiin. Tässä raportissa tarkastellaan työpaketti 2.2:n tuloksia.

Kohonneita radonin ja muiden radionuklidien pitoisuuksia esiintyy eurooppalaisissa pohjavesissä pääasiassa Skandinavian laajoilla kiteisten kivilajien alueilla, erityisesti Suomen ja Ruotsin graniittialueilla, mutta myös

suppeimmilla Keski- ja Etelä-Euroopan kiteisten kivilajien alueilla, Ukrainassa ja Skotlannissa. Eri ilmastusmenetelmien (hienokupla-, torni- ja suihkutusilmastuksen) ja kaupallisten ilmastimien radoninpoistotehokkuutta tutkittiin monissa suomalaisissa, ruotsalaisissa ja saksalaisissa vesilaitoksissa. Osa näissä laitoksissa käytetyistä ilmastusmenetelmistä oli suunniteltu radonin poistoon mutta osa Fe:n, Mn:n, CO_2:n tai H_2S:n poistoon. Raakavesien radonpitoisuudet vaihtelivat näillä laitoksilla 8 – 5 800 Bq/l.

Yhdistetty hienokupla- ja suihkutusilmastus poisti 98% radonista yhdellä vesilaitoksella, joka oli suunniteltu erityisesti radonin poistoon. Radonin poisto oli hyvin tehokasta (88 – 99%) myös useimmilla torni-ilmastimia käyttävillä vesilaitoksilla, kun taas suihkutusilmastuksella saavutetut poistumat vaihtelivat laajemmissa rajoissa (67 – 98%). Useimpien vesilaitosten suihkutusilmastuksen tehokkuutta voidaan tarvittaessa parantaa yksinkertaisilla toimenpiteillä. Erityyppisiä kaupallisia ilmastimia, jotka on suunniteltu alunperin yksityistalouksien käyttöön, voidaan käyttää tehokkaasti (67 – 99%) myös pienillä vesilaitoksilla. Fe:n, Mn:n, CO_2:n tai H_2S:n poistoon suunnitelluilla ilmastimilla saavutetut radonin poistumat vaihtelivat laajoissa rajoissa (13 – 98%). Torni-ilmastimella tehdyissä pilot-kokeissa saavutetut radonin (85%) ja CO_2:n (75%) poistumat olivat lähes samansuuruisia, mikä on sopusoinnussa vesilaitoksilta saatujen tulosten kanssa. Käytännöllisesti katsoen kaikki uraani saatiin poistettua yhden vesilaitoksen vedestä, kun sen poistoon käytettiin vahvaa orgaanista anionihartsia.

Contents

Preface

The shared-cost research project "Treatment Techniques for Removing Natural Radionuclides from Drinking Water" (TENAWA) was carried out in the fourth Framework Programme 1994–98 of research and training funded by the European Commission in the sector of Nuclear Fission Safety. The aim of the TENAWA project was the evaluation of treatment techniques for removing natural radionuclides from drinking water. It was carried out by the following partners:

1. STUK—Radiation and Nuclear Safety Authority, Finland
2. BALUF—Federal Institute for Food Control and Research, Austria
3. PUMA—Philipps University Marburg, Nuclear Chemistry, Germany
4. IWGA—Control University of Agriculture, Department for Water and Wastewater Engineering, Industrial Waste Management and Water Pollution, Austria
5. SSI—Swedish Radiation Protection Institute, Sweden
6. ESWE—Institute for Water Research and Water Technology, Germany
7. HYRL—University of Helsinki, Laboratory of Radiochemistry, Finland

The TENAWA project was divided into 13 work packages:

WP 1.1: General Considerations: Literature Survey on Natural Radioactivity in Drinking Water and Treatment Methods in European Countries
WP 1.2: General Considerations: Intercomparison of Analysis Methods
WP 1.3: General Considerations: Definition and Classification of Different Water Types and Experimental Conditions
WP 2.1: Removal of Radon by Aeration: Testing of Commercially Available Equipment for Domestic Use
WP 2.2: Removal of Radon by Aeration: Testing of Various Aeration Techniques for Small Waterworks
WP 3.1: Removal of Radionuclides from Private Well Water with Granular Activated Carbon (GAC): Removal of Radon
WP 3.2: Removal of Radionuclides from Private Well Water with Granular Activated Carbon (GAC): Removal of U, Ra, Pb and Po
WP 4: Removal of Radioactivity by Methods Used for Fe- and Mn-removal from Private Wells

WP 5.1: Removal of U, Ra, Pb and Po by Ion Exchange Methods. Removal of U and Po from Private Ground Water Wells using Anion Exchange Resins
WP 5.2: Removal of U, Ra, Pb and Po by Ion Exchange Methods. Removal of Ra and Pb from Private Ground Water Wells using Cation Exchange Resins
WP 6: Removal of U, Ra, Pb, and Po with Adsorptive or Membrane Filters
WP 7: Speciation of U, Ra, Pb and Po in Water
WP 8: Disposal of Radioactive Wastes by Water Treatment Methods: Recommendations for the EC.

Many discussions have taken place among our colleagues in and beyond the TENAWA project and we gratefully acknowledge these. We also wish to thank all the companies and the house owners for the good cooperation during the project.

1 Introduction

Elevated levels of radon and other natural radionuclides in European ground waters have been found mainly in wide areas of the crystalline Scandinavian bedrock. The highest concentrations in Europe have occurred in bedrock waters in the granite rock areas of Finland and Sweden. Crystalline rock areas exist also in parts of Central and Southern Europe, Ukraine and Scotland. Also in these areas elevated levels of radionuclides have been found in the areas of granitoids.

Studies from USA and also from Europe indicate the elevated levels of radon and other radionuclides in drinking water are mainly the problem of small ground water aquifers (Hess et al.,1985, Kulich et al.,1988). The average levels of radionuclides are usually lower in the bigger ground water aquifers than in the smaller ones. Thus radon removal is firstly needed in private homes and small waterworks, which derive water from small ground water aquifers.

In Finland and Sweden radon should be removed from tens of thousands of private wells, if the same regulations would be applied to the private wells as to the public water supplies. The great need of radon removal equipment in these two countries is due to the large, sparsely populated areas, where people live far away from public water supplies and where drilled wells have become more and more popular in the recent tens of years. Also waterworks consider bedrock water a suitable alternative to surface water or to other ground water sources, if they are too far away or inadequate. In Finland the usage of bedrock water could be increased considerably, since 70% of its groundwater is estimated to lie in bedrock (Lonka et al.,1993).

The comprehensive surveys of the Finnish and Swedish public water supplies have indicated that radon removal is needed mainly from bedrock water and only rarely from ground water in soil. The number of waterworks, which should remove radon from water, is presently known to be below twenty in Finland but a few hundreds in Sweden. The big difference in these numbers can be explained by the difference in the radon levels allowed for public water supplies (i.e. 300 Bq/l in Finland and 100 Bq/l in Sweden) but also by the greater use of bedrock water in Sweden. It seems also to be more frequent in Sweden than in Finland, that a group of houses or even entire villages have a common water supply from the same well. Many Finnish waterworks have also explored alternative water sources in order to replace radon-rich water with better water, especially if also other water qualities have not been attained. One reason to this has also been the scarcity of the knowledge, how to apply aeration efficiently for radon removal. The maximum radon levels in the Finnish and Swedish waterworks have varied between 1 000 and 2 500 Bq/l. All these waterworks cannot be considered small, since some of them supply water to hundreds of houses.

Concentrations in German drinking water are generally lower than in Sweden or Finland [Rühle 1996]. The median of over 1100 water samples is 6 Bq/l and maximum 1500 Bq/l. These samples were taken both from private households and from raw waters in waterworks. Due to the geological situation only small areas exist in Germany, where waterworks recover raw water with radon contents higher than 400 Bq/l [Raff et al. 1998, Bünger et al. 1993]. These areas are in Erzgebirge (Saxony), Fichtelgebirge (Bavaria) and Rhine-Nahe-Area (Rheinland-Pfalz/Rhineland-Palatinate). Additionally in some other areas a few raw waters with radon contents in the range of 100 Bq/l were found: Schwarzwald or Black Forest (Baden-Württemberg), Bayerischer Wald or Bavarian Forest (Bavaria), Oberpfälzer Wald (Bavaria) and Harz Mountain (mainly Lower Saxony).

Erzgebirge, Fichtelgebirge, Bayerischer Wald and Oberpfälzer Wald belong to the Bohemian Massif, a hercynian crystalline complex. The granite and gneiss rocks in this area are known to contain many uraniferous deposits. Black Forest and Harz Mountain are also crystalline areas containing granites. In the Rhine-Nahe-Area some small-scaled rhyolite massifs exist which are also known to contain uraniferous deposits. Additionally the Rhyolite of Bad Kreuznach is known as aquifer for radon-rich water for radon baths.

The situation in other European countries is not known exactly. In some countries, like in Austria, more intensive surveys are under way to find out the situation. In some other countries monitoring of radionuclides in public and private ground waters will be required to find out, if radionuclide removals from water will be required. The knowledge on the treatment technology for removing radon from small waterworks supplies may be in greater demand in the future than today due to the increased interest in new, good-quality ground water sources.

The first aim of this WP is to design and test different aeration techniques for radon removal, to compare their cost-effectiveness and to write guidelines how to build aeration systems. In that purpose one waterworks, where radon removal was based on spray and diffused bubble aeration, was designed and installed in Finland and experiments were made in Germany with a counter current packed tower column in half technical scale to evaluate its ability to remove radon and carbon dioxide. Besides radon removal, uranium removal was also accomplished in this Finnish waterworks.

The second aim of this project was to compare the different aeration techniques already applied for radon removal in waterworks in Sweden, Finland and Germany. The data on the radon removal efficiencies, on the descriptions of the aeration principles and on the other water treatments applied simultaneously with radon removal are presented for several waterworks from these three countries. The most important water quality parameters have been determined in raw and treated water of the Finnish waterworks to see the effect of the water treatment on its quality. The evaluation of this data will provide useful information for the designing of new plants. In most of the waterworks studied now, aeration was applied together with other water treatments. In Finland and Sweden typical treatments are the removal of Fe, Mn or humus or to alkalise too acidic and soft waters. In Germany the typical water treatment in the areas, where increased radon levels occur in groundwater, is de-acidifying, but also Fe and Mn removal is needed. In designing the aeration techniques for radon removal, the other water treatment processes should thus be considered very often.

The third aim of this project was to collect data on radon removal efficiencies in those waterworks, which apply aeration for removing Fe, Mn, CO_2 or H_2S. The evaluation of this data would provide valuable information for designing of the treatment processes for new waterworks and for improving the existing processes. For this purpose water samples from the raw and treated water was collected from several waterworks in Finland.

2 Designing and testing of various aeration techniques for small waterworks

2.1 Radon and uranium removal systems in the Länkipohja waterworks in Finland

Vartianen Oy (VAR), HOH Seportec Oy since 2001, has designed and installed an aeration system for Rn removal and an ion exchanger for U removal for the Länkipohja waterworks in Längelmäki commune in Southern Finland. In addition to these treatments also Mn and hardness are removed from the water. This waterworks supplies water to 350 inhabitants in the centre of the village. The installation of the plant was carried out in August 1997 when the construction of the necessary building was completed. The pilot plant tests were carried out before the final designing of the treatment systems. The system is dimensioned for the raw water flow of 0.5 -12 m^3/h, for a maximum total water consumption of 110 m^3/day and for a normal water consumption of 70 m^3/day.

2.1.1 Aerator for radon removal

Combined sprayed and diffused bubble aeration is applied for Rn removal. Aeration is carried out in a cylinder tank (cylinder volume 3 m^3 and diameter 1500 mm, water volume 2.5 m^3). Raw water is sprayed into the tank through four water spraying nozzles located in the top of the tank about 30 cm above the water level. Four aeration nozzles placed in the bottom of the cylinder accomplish diffused bubble aeration. The water throughput in the aerator is about 7 m^3/h and the air consumption 80 m^3/h. Thus air/water ratio is 11. The aerated water is discharged into a 30 m^3 storage basin (under the building), from where the water is pumped to the network of water pipes in the village. The radon-rich air from the aeration tank is directed through a pipe to the roof of the building.

2.1.2 Ion exchangers for U, Mn and hardness removal

U, Mn and hardness are removed with a separate anion and cation exchangers. The raw water flows first into the cation exchanger, secondly into the anion exchanger and finally to the aeration cylinder. The volumes of the cation and anion masses are both 200 litres. The resins are the ORWA resins normally used in VAR's commercial ion exchangers for Fe, Mn and humus removal. In this EU-project the same resins are tested in WP5 for removing of U, Ra, Pb and Po from waters in domestic filters. These resins are strong acid cation and strong base anion resins. The cation exchanger is equipped with a by-pass pipe. The ion exchangers are regenerated automatically every night with a saturated sea salt solution, from a separate cylinder. A maintenance man adds sea salt to the cylinder once a week.

The whole treatment process is fully automatic and directed by a control unit, which sends an alarm to a maintenance man's mobile phone or beeper, if there is some dysfunction in the treatment process. In spite of this the maintenance man goes to the waterworks daily.

2.1.3. Results from radionuclide and water quality analyses

The results from the radionuclide analyses are presented in Table 1. The analyses have been performed several times during the course of this project. The results of analyses have indicated that radionuclides have always been removed with high efficiencies, thus only results of one analysis are presented here. The concentration of radon was 330 Bq/l in the raw water and 12 Bq/l in the aerated water during the two samplings that were carried out in August and September 1997. Thus the radon reduction is 96.4%.

The U content was 0.138 mg/l in the raw water, after the cation exchanger 0.131 mg/l and then after the anion exchanger 0.0002 mg/l. A minor amount of U (5%) could also be removed by the cation exchanger, which is installed before the anion exchanger. This difference could also be due to the total error of the determinations. Anyhow, if the cation exchanger has removed U, it is possible because U may exist also as cationic complexes. These results indicate that practically all of U is removed (99.9%) by the ion exchangers.

The small amount of Ra, which occurs in the water, seem be removed by anion exchanger but not by the cation exchanger as expected. This can be explained by the fact that Ra would exist in this water mainly as anionic complexes. Because the statistical errors (50 - 60%) of the Ra results (detection limit 0.01 Bq/l) are big due to the low concentrations of Ra (0.02 - 0.03 Bq/l), no definite conclusions can be made on the basis of these results.

The minor amounts of ^{210}Pb and ^{210}Po, that occurs in raw water, seem not to be removed by the anion or cation exchangers. This is in agreement with the results obtained by the same resins in domestic use (WP 5). Poor removal of these elements with ion exchangers can be explained by the speciation. The speciation studies have shown, that lead and polonium occur in Finnish ground waters mainly bound to various sizes of particles, nor in ionic form (WP 8). They could thus be removed rather by adsorptive methods than by ion exchangers. Table 1 also show that the concentrations of ^{210}Pb and ^{210}Po are decreased during the aeration. This could be explained by the precipitation or uneven distribution of particles in the aerator. The amounts of ^{210}Pb and ^{210}Po in raw water are however quite low, and therefore their removal by these treatment methods has mainly scientific interest and need not be studied owing to radiation protection.

Table 1. Radionuclide concentrations in raw and treated water in Länkipohja waterworks since the equipment for removing of Rn, U and hardness have been installed by VAR.

Date of Sampling	14.8.1997	15.9.1997						
Sample	^{222}Rn Bq/l	^{222}Rn Bq/l	^{238}U Bq/l	^{234}U Bq/l	U mg/l	^{226}Ra Bq/l	^{210}Pb Bq/l	^{210}Po Bq/l
Raw Water	330	330	1.71	3.04	0.138	0.017 (2	0.078	0.017
After Cation Exchange			1.61	2.90	0.131	0.031 (2	0.080	0.012
After Anion Exchange			0.003 (1	0.004 (1	0.0002	<0.01	0.072	0.025
After Aeration	12	12	0.0007 (1	0.002 (1	0.001	<0.01	0.004	0.001

1) error ± 40%
2) error ± 50–60%

The values of various water quality parameters in the raw and treated water are presented in Table 2. The raw water analyses have been carried out several times but the treated water only twice after the installation of the radionuclide removal systems in August 1998. The communal health officers have their own regular sampling programs for controlling the water qualities. Those results are not presented here. Table 2 shows that the water treatment has changed some parameters. No clear growth of bacteria has been observed. The acidity of the water has decreased after the aeration, evidently by the removal of CO_2.

The water quality has been improved due to the removal of Mn by the cation exchanger and due to the removal of SO_4 by the anion exchanger. Small amounts of organic matter, that occurred in the raw water, were partly removed by the anion exchanger, and its amount in the treated water was low (1 mg/l). The increase of Na and Cl always occurs as a result of the regeneration, which takes place in Länkipohja every night with saturated sea salt solution. VAR

Table 2. Physico-chemical water quality in the waterworks of Länkipohja in Längelmäki.

Parameter	Unit	Raw water				Raw water	Ion exchanged	Ion exchanged and aerated water	Raw water	Ion exchanged	Ion exchanged and aerated water
Date		22.10.94	29.3.95	25.9.95	8.11.95	15.9. 97	15.9.97	15.9.97	4.3.98	4.3.98	4.3.98
Heterot. 35 °C	cfu / ml	-	-	-	-	10	14	31	2	5	3
Heterot. 22 °C	cfu / ml	1	4	0	0	0	5	11	10	42	44
Coliformic 35 °C	cfu /100ml	0	0	0	0	-	-	-	-	-	-
Colour	Pt mg/l	5	5	5	5	-	-	-	-	-	-
pH		7,5	7,5	7,5	7,3	7,6	7,4	8,0	7,5	7,4	8,0
Acidity	mmol/l	-	-	-	-	0,16	0,12	0,02	-	-	-
Alkalinity	mmol/l	-	-	-	-	3	2,2	2,2	3,1	2,1	1,8
Tot.hard. (Ca + Mg)	mmol/l	1,8	1,7	1,8	1,8	1,8	0,1	0,14	1,7	-	0,33
Conductivity	mS/m	-	42	41	-	41	45	46	42	46	48
Turbidity	FTU	-	-	-	-	<0,05	<0,05	<0,05	<0,05	<0,05	<0,05
$KMnO_4$	mg/l	1,9	3,5	3,2	1,9	3,2	<1	1,4	-	-	-
TOC	mg/l	-	-	-	-	-	-	-	1,7	1,1	1,0
Na	mg/l	-	-	-	-	18	96	96	19	100	88
K	mg/l	-	-	-	-	-	-	-	1,4	0,44	0,67
Mg	mg/l	-	-	-	-	-	-	-	16	0,07	3,1
Ca	mg/l	-	-	-	-	-	-	-	48	0,12	8,9
Fe	mg/l	0,02	<0,01	<0,01	0,03	0,003	<0,002	<0,002	<0,002	<0,002	<0,002
Mn	mg/l	0,02	0,03	0,07	0,03	0,11	0,006	0,006	0,049	0,001	0,004
Cl	mg/l	-	28	28	-	24	39	40	24	61	66
F	mg/l	-	-	-	-	0,30	0,30	0,29	0,32	0,31	0,30
NO_3-N	mg/l	-	<0,2	< 0,2	-	<0,1			<0,1	<0,1	<0,1
PO_4-P	mg/l	-	-	-	-	<0,005	<0,005	<0,005	<0,005	< 0,005	<0,005
SO_4	mg/l	-	-	-	-	18	<1	1,4	18	<1	1,1
NH_4	mg/l	-	<0,10	<0,10	-	<0,01	<0,01	<0,01	-	-	-
O_2	mg/l	-	-	-	-	2	2	12	1,5	1,8	13

- not determined

usually tests during the first year after the installation, which is the best regeneration interval to attain the best water quality. This can be done in Länkipohja, and possibly the regeneration interval can be longer and be carried out only every second or third night or even more seldom. On account of U, it is not necessary regenerate every night because only 0.07 % of theoretical capacity of the anion mass (12.7 kg of U) is used during a day. When the regeneration interval is changed, the water qualities will be analysed to find out if the Na and Cl contents have decreased. Anyhow, their values in the treated water are now lower than the maximum permissible values set in the Finnish drinking water regulations (max. Na = 200 mg/l, max. Cl = 250 mg/l).

The treated water is quite soft (tot. hard. = 0.1 mmol/l), because Mn and hardness has been removed by the cation exchanger. Although the water was not hard (raw water tot. hard. = 1.8 mmol/l), the inhabitants in the village wanted to have water softening when the waterworks was designed. STUK and VAR together with the health offices of the commune organised a meeting in February 1998 for the people living in the village in order to inform them on their drinking water quality and ask once more their opinion, if the water softening will be continued. Their opinion was that water hardness should not be increased. By increasing the water flow in the bypass pipe of the cation exchanger the hardness can be increased easily without decreasing the removal of U and Rn. Anyhow, the cation exchanger is necessary to reduce Mn under the maximum value (0.05 mg/l) set in the Finnish drinking water regulations.

2.1.4. Waste disposal at the Länkipohja waterworks

Uranium-rich and saline wastewaters are produced in Länkipohja waterworks. The wastewaters are treated in the municipal wastewater treatment plant. After the treatment waters are released to a lake and the sludge is stored at the municipal waste disposal site.

Calculations show that 9.1 g of U is released to the wastewaters during the regeneration of the anion resin every day. This means the total amount of U in the waste sludge produced yearly in the treatment plant is 3.3 kg (from Länkipohja waterworks). If all that waste is disposed to the same waste area, the U content in the area will be increased.

The following assumptions can be made to calculate the yearly increase of U in the waste area:

- The area of the disposal site is 5 000 m^2
- All U is retained in the sludge (none to waste waters)
- The average U content of the soil in Finland is 38 Bq/l (3.1 mg/kg)
- The soil density is 1.6 kg/dm^3
- The soil depth where the increase is estimated as 50 cm

In this example the yearly increase of U in that amount of soil mass (as assumed above) is 27%. However, if U is not removed from the water, the same amount of U will come to the waste treatment plant by assuming that the same raw water is consumed in the village.

2.2. Removal of radon by counter-current packed tower aeration (pilot plant) in Germany

Experiments were made at a counter-current packed tower column in half-technical scale to evaluate its ability to remove radon and carbon dioxide from water. In such equipment water flows through the column downstream while air is blown upstream (Figure 1). The filling rings form a large surface where dissolved gases transfer from liquid to gaseous phase.

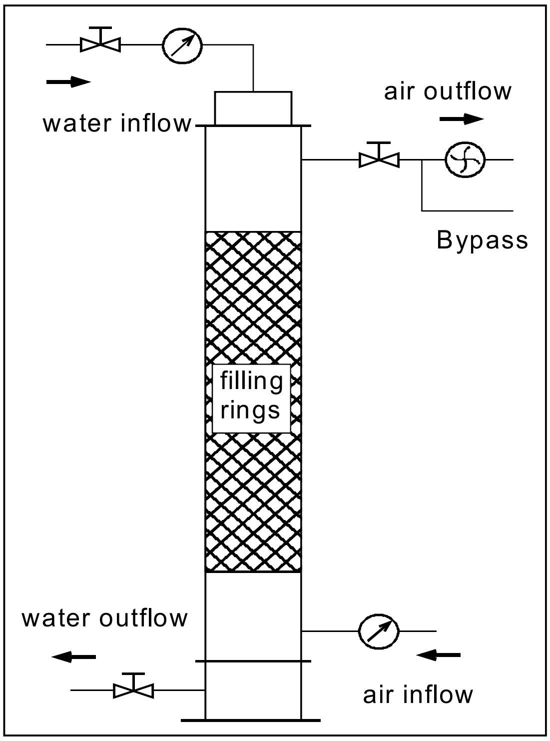

Figure 1. Scheme of a counter-current packed tower column.

Water with a radon content of 1000 Bq/l and a carbon dioxide content of 1 mmol/l (44 mg/l) was used for the experiments. The column was 150 cm high and had a diameter of 19 cm. In several experiments it was filled with four different filling rings (Norpac PP 25 mm, Bialecki Metall 25 mm, Pall PP 25 mm and Pall PP 15 mm) out of metal or polypropylene. The filling height in the column was 1 m. By using throughputs of 1 to 4 m^3/h (35 to 140 m^3m-2h-1) and air/water ratios up to 40 removal efficiencies of 85% were achieved (Figures 2 and 3).

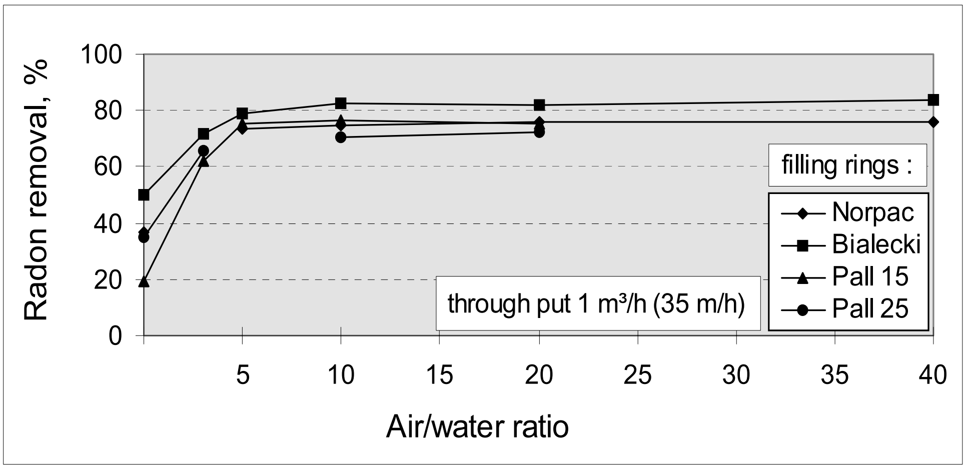

Figure 2. Radon removal with different filling rings depending on the air/water ratio.

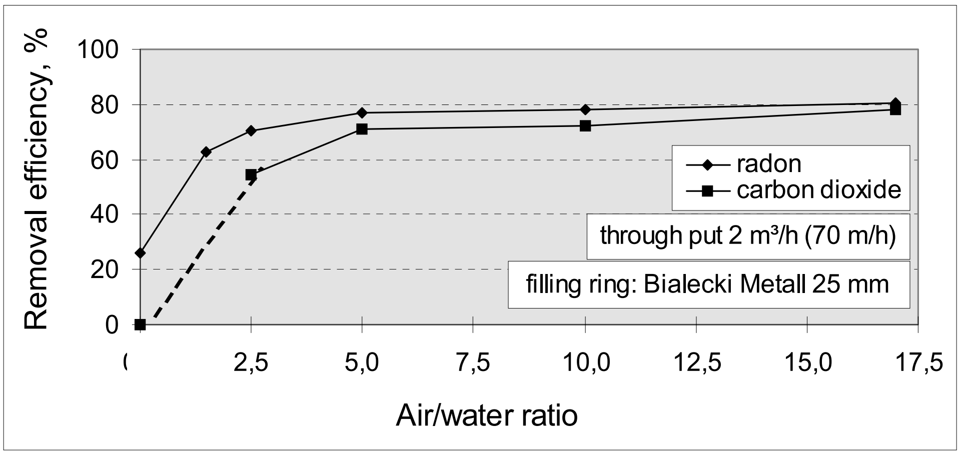

Figure 3. Radon and carbon dioxide removal depending on the air/water ratio.

From a packed tower column radon or carbon dioxide-rich air can be diverted directly out of a waterworks building. The tested column in half-technical scale removed 85% of the water-dissolved radon. By using a typical filling ring heights of two to three meters in a practical application in waterworks a removal efficiency of 95% can be expected. Additionally the experiments showed:

- high radon removal efficiencies were attained by using as low air/water ratios as five
- carbon dioxide and radon showed a very similar removal behaviour

3 Radon removal efficiencies attained by various aeration methods in Finnish, Swedish and German waterworks

3.1 Results from Finnish waterworks designed for removing radon and other elements (Fe, Mn)

Table 3 shows the Rn removal efficiencies of seven Finnish waterworks. The results of their water qualities in raw and treated water are presented in Table 2 (for Länkipohja) and 4 (six other waterworks). Three waterworks apply commercial aerators for radon removal. Only short descriptions on these waterworks and on their treatment processes are presented here.

3.1.1 Descriptions on the waterworks and their treatment processes

The results of the **Länkipohja** waterworks in Längelmäki commune and the removal process have been discussed in the previous chapter.

The **Metsäserla** waterworks in Lohja commune is owned by a pulp and paper factory. This waterworks derives water from a drilled well to be used as drinking water in the factory and in the nearby residential area. The process water in the factory is derived from a nearby lake. In addition to their own drill well water the Metsäserla waterworks can also use the municipal water of Virkkala commune. The alternative water supply is needed during the maintenance and repair work.

In this waterworks Rn, Fe and Mn are required. Rn removal is based on spray aeration and Fe and Mn removal on ion exchange.

The water is filtered at first through the cation exchanger in order to remove Fe and Mn. Rinse and regeneration water for the filter is taken from the pressure line after the aeration. The cation exchanger will be regenerated from time to time by the treated water.

The aeration is carried out by spraying the water (1 800 Bq/l Rn in raw water) to the basin (15 m^3) through five adjustable nozzles. The nozzles are directed upwards allowing as long a contact time with air as possible. With the help of the channel blower, a slight overpressure is blown to the air space between the water level and the nozzles. The purpose of the overpressure is to prevent the transfer of radon to the water falling into the basin. The level control of the aeration basin controls the drill well pump.

The **Pohjukansalo** waterworks is a communal waterworks in the commune of Leppävirta, and it supplies water to 6 000 inhabitants. Its water treatment capacity is 600 - 700 m^3 per day. It takes raw water from three drilled wells (Rn vary between 300 and 1 100 Bq/l) and from a lake. The Rn content of the mixed raw water from drilled wells has varied between 720 and 740 Bq/l. At this time three kind of water is delivered to the inhabitants: 1) treated water from the drilled wells 2) treated water from drilled wells mixed with lake water and 3) lake water. Lake water has its own treatment plant. During 1999 new wells (3 - 5) were drilled to replace the usage of lake water in this village.

In this waterworks Rn, Fe and Mn removals are required. Rn removal is based on packed tower aeration and Fe and Mn removal on slow sand filtration.

A packed tower aerator is applied for Rn removal and also to oxidising Fe and Mn. Besides this, a chemical oxidising of Fe and Mn is also required. Therefore $KMnO_4$ is dosed to water before two separate sand filtering basins (area of each of them 10 m^2, max. surface load 2.3 m/h), where removal of Fe and Mn hydroxides is performed. Liquid chlorine is dosed to the water before and after the sand filtration. The pH of water should also be increased and it take place in a mixing tank, where NaOH is added. Finally water is pumped from the storage basin to the water tower, where also lake water is pumped from its own treatment plant.

The **Pipola** waterworks in Karjalohja commune provide water to an establishment, where disabled people are living. It also derives raw water from a drilled well. The Rn concentration of the drilled well has varied between 5 400 and 6 000 Bq/l in the course of years. A commercial aerator (RF-225/KR6 from Watman Oy company) produce continuously treated water into the large storage tanks (three 2 m^3 tanks). This aerator is based on a spray aeration technique. The submersible pump feeds water through an ejector into the aeration tank. A cyclone inside the aeration tank transforms the water into small droplets that have a very large surface area. In this waterworks the volume of the aeration tank is 225 litres and the aeration time 4 minutes. The efficiency of the aeration depends on the power of the booster pump (type KR6 in this case): the greater the pressure created the better Rn removal. The operation principle of this aerator is presented more definitely in Final report of WP 2.1.

The **Kirkonkylä** waterworks is also a communal waterworks in the commune of Kihniö. The raw water is pumped from two drilled wells. The concentration of radon in raw waters have been between 460 and 840 Bq/l. It supplies water to 1 100 inhabitants. The treatment capacity of the waterworks is 250 m^3 per day.

In this waterworks Rn, Fe and Mn removals are required. Rn removal is based on spay aeration and Fe and Mn removal on slow sand filtration.

Raw water is spayed through Dresden nozzles onto the gravel filter basin, after that it flows through two slow sand filtration basins (area of 54,8 m^2), where Fe and Mn are removed. Finally water flows through level control basin into the storage basin.

The **Storby Vatten** in Eckerö commune in Ahvenanmaa supply water to 120 persons. It derives water from two drilled wells. The concentration of radon in raw water has varied between 660 and 1 050 Bq/l during different samplings. Manganese removal is also required.

A commercial aerator of type BAQ-Kombi 1A from Bontec company in Sweden is used for Rn and Mn removals. This aerator is based on a spray nozzle aeration technique, and the aeration is accomplished in a 100 litres tank, which is made of black polyethene plastic stregthened with fiber glass. Raw water pump feeds water from the pressure tank through a mechanic valve into an aeration tank. After that a submersible pump takes water from the bottom of the aeration tank and feeds it through three aeration nozzles. A fan removes radon-rich air to the outdoor air through a ventilation channel. The air throughput is 25 m^3/h. The maximum capacity of the aerator is 20 l/min in a continuous use but 40 l/min temporarily. Thus its air/water ratio is 25 in a continuous use.

Fe and Mn are removed by circulating water through a filter media inside the aeration tank (sand and other components if also organic matter is to be removed), which is backwashed either manually or automatically.

The **Solbacka Vatten** in Saltvik in Ahvenanmaa supply water to 50 persons. It derives water from a drilled well. The concentration of radon in raw water has varied between 640 and 1 700 Bq/l during different samplings.

A commercial aerator of type BAQ 1A from the same Swedish company, Bontec, is used for Rn removal as in Storby Vatten. This aerator is not equipped with filter mass because the removal of Fe or Mn is not required.

3.1.2 Results on determination of radon removal efficiencies and water qualities

Table 3 shows that the Rn removal has been efficient enough in these seven waterworks considering the Finnish regulation (max. Rn 300 Bq/l). The concentrations of radon in raw waters of different waterworks have varied from 330 to 5 800 Bq/l and in treated waters from 10 to 250 Bq/l. Table also show that in some waterworks the concentrations of Rn in raw waters have varied much

Table 3. Radon reduction (%) as attained by various aeration methods in seven Finnish waterworks, where radon removal has been accomplished.

Waterworks/ commune	Aeration method	Other water treatments needed	Throughput (m^3/d)	Sampling date	^{222}Rn Raw	(Bq/l) Treated	Re-duction (%)
Länkipohja / Längelmäki	Spray nozzle and diffused bubble aerator	U, Mn and hardness removal, Cation/anion exchanger	70	14.8.97 25.5.98 7.10.98	330 360 360	10 10 10	96 97 98
Metsäserla/ Lohja	Spray nozzle aerator	Fe and Mn removal Cation exchanger	70	8.8.95 17.10.96 14.10.98	1800 - 1840	- 210 210	- - 88
Pohjukansalo/ Leppävirta	Packed tower aerator	Fe and Mn removal Oxidation with KMnO4, dolomite limestone filtration	725	12.1.98 28.10.98	740 720	90 80	88 89
Pipola/ Karjalohja	Spray aerator Commercial aerator, WatMan, RF-225 /KR6	No other water treatment	8	8.10.97 11.12.97 13.8.98 30.9.98	5800 - - -	100 140 130 140	98 98 98 98
Kirkonkylä/ Kihniö	Spray nozzle aerator	Neutralisation with NaOH, gravel and slow sand filtration	160	2.2.95 2.12.96 3.11.98	460 - 840	- 230 250	- - 70
StorbyVatten/ Eckerö	Commercial spray nozzle aerator, Bontec, BAQ-Kombi 1A	Fe and Mn removal by sand-filter (backwash) in BAQ-Kombi 1A	30	13.2.96 5.6.96 17.12.98	1050 - 660	- 220 67	- - 90
Solbacka Vatten/ Saltvik	Commercial spray nozzle aerator, Bontec, BAQ 1A	No other water treatment	60	28.8.95 17.12.98	1700 640	- 210	- 67

at various sampling times. Therefore it important to dimension the new systems efficient enough to reduce even much higher radon levels than measured until then.

Table 3 indicate that the radon removal efficiencies in most waterworks have been between 88 and 98% and in two waterworks about 70%. The best efficiencies were attained in Länkipohja, where aeration was accomplished by using both spay and diffused bubble aeration and in Pipola, where a commercial aerator was used. It is quite probable that the aeration can still be improved in some of these waterworks. This is possible at least in the Metsäserla waterworks and in the Kirkonkylä waterworks at Kihniö, where spray nozzle aeration is applied. In these waterworks the improvements can be accomplished quite easily, if better radon removal is aquired.

Table 4 indicate that other water qualities have been improved mainly by removal on Fe, Mn and carbon dioxide. No water quality parameter reported here has indicated that water quality had been impaired by the various treatments.

Aeration has removed carbon dioxide with about the same efficiency as radon. The calculations show that the only exceptions were the Kirkonkylä waterworks at Kihniö, where the carbon dioxide removal efficiency is only 25% but radon removal efficiency 70%, and the Metsäserla waterworks, where the carbon dioxide removal efficiency is 76% and radon removal efficiency 88%. In the other waterworks, from where carbon dioxide contents were determined, the differences between the carbon dioxide and radon removal efficiencies were only from 2 to 5%; usually the radon removal was a little more efficient than carbon dioxide removal. These latter results are in good agreement with the results that ESWE has attained, when radon and carbon dioxide removals were studied by using a packed tower aeration (Figure 3). The tests in some Finnish waterworks should be repeated to verify if radon and carbon dioxide removals will be quite equal independently of the aeration technique applied.

Iron and manganese have been removed very efficiently in most of the waterworks studied here. Their contents in the treated waters were usually very low. The iron and manganese removal methods have not impaired the other water qualities. The radon aerator in the Pipola waterworks has also removed 90% iron, whereas manganese removal was there much more ineffective. It seems also that the filter media used in the BAC Combi aerator for manganese removal in the Storby waterworks has increased the sodium level but decreased nitrate level in the treated water. However further measurements would be required to verify these effects.

Table 4. Physico-chemical water quality in six Finnish waterworks where radon removal has been accomplished.

Parameter	Unit	Metsäserla / Lohja		Pohjukansalo / Leppävirta		Pipola / Karjalohja				Kirkonkylä / Kihniö		Storby Vatten / Eckerö		Solbacka Vatten / Saltvik	
		Raw water	Treated water	Raw water	Treated water	Raw water	Treated water	Raw water	Treated water	Raw water	Treated water	Raw water	Treated water	Raw water	Treated water
Sampling date		14.10.1998	14.10.1998	28.10.1998	28.10.1998	8.10.1997	8.10.1997	30.9.1998	30.9.1998	3.11.1998	3.11.1998	17.12.1998	17.12.1998	17.12.1998	17.12.1998
Heterot. 35 °C	cfu / ml	0	2	-	-	-	-	0	2	-	-	-	-	-	-
Heterot. 22 °C	cfu / ml	4	1	-	-	1	9	2	2	-	-	-	-	-	-
Coliformic 35 °C	cfu/ 100ml	2	0	-	-	1	1	-	-	-	-	-	-	-	-
pH		7,6	8,1	6,7	7,7	8,2	8,3	8,1	8,2	7,5	7,6	7,5	8,0	7,6	7,8
Alkalinity	mmol/l	3,8	3,7	0,94	1,2	-	-	-	-	2,4	2,3	5,5	5,5	4,1	3,8
Tot.hardness (Ca + Mg)	mmol/l	-	-	0,76	0,88	0,55	0,56	0,56	0,56	1,7	1,6	2,7	1,9	2,2	2,0
Conductivity	mS/m	58	58	21	23	-	-	25	22	38	39	65,3	66,1	50,6	46,6
$KMnO_4$	mg/l					2	1,7	-	-			10	10	5,7	5,1
TOC	mg/l	2,2	2,2	1,5	1,4	-	-	0,9	0,9	2,8	2,1	-	-	-	-
Na	mg/l	52	50	18	18	-	-	31	32	13	14	37	72	22	26
Fe	mg/l	0,50	0,19	0,16	0,002	0,068	0,007	0,015	0,004	0,46	0,009	0,07	<0,05	<0,05	<0,05
Mn	mg/l	0,22	0,069	0,42	0,001	0,033	0,028	0,04	0,023	0,44	<0,0005	0,40	<0,03	<0,03	<0,03
Cl	mg/l	65	55	7,8	7,9	-	-	5,9	6	33	34	35	35	23	16
F	mg/l	0,50	0,47	0,38	0,39	-	-	1,2	1,2	0,55	0,53	1,3	1,3	2,3	2,5
NO_3-N	mg/l	-	-	<0,1	<0,1	-	-	<0,1	<0,1	<0,1	<0,1	0,61	0,38	2,9	2,3
SO_4	mg/l	-	-	57	59	-	-	13	13	28	29	31	31	32	28
CO_2	mg/l	5,3	1,3	10	1,3	-	-	-	-	5,3	4,0	12	<1	5,0	1,9
O_2	mg/l	2,7	11	-	-	-	-	-	-	-	-	-	-	-	-

3.2. Results from Swedish waterworks designed for radon removal

SSI has compiled some data on small waterworks in Sweden, where aeration systems for removal of radon have been installed. The manufacturer or the owner of the waterworks has performed the Rn measurements. Part of them is listed in Table 5. Several types of aeration systems have been installed but only the test results of three types of aerators are presented here. One interesting type of equipment is the packed column aerator, which has a very high capacity to remove radon from large volumes of water. One company in Sweden, Kemidepån, has recently installed three packed tower aerators in small waterworks. The equipment is imported from the Czech Republic and slightly modified for better efficiency. The Czech name is Ekomonitor Aerating Tower, whose results are presented in Table 5. The results are very good so far.

Other types of aerators common to small waterworks are up-scaled versions of aerators originally designed for removal of radon from private well water. In one municipality in the north-western Sweden three small waterworks have installed Libradon aerators to reduce the radon levels. The municipality has made a series of measurements of the radon concentrations in raw water and treated water at these installations and the most recent results are shown in Table 5.

Another company, which has made several installations in different areas of Sweden, is Ekoteknik. Their aerator is called Radon-X. The results on certain waterworks having this aerator are presented in Table 5.

Waterworks for public water supplies in Sweden can have financial support for remedial actions to reduce the radon concentration in the water delivered to the consumers. This financial support is allowed when the radon concentration in the consumer water is 100 Bq/l or higher. The money is intended to cover the total costs from the installation of a commercial aerator or other radon reduction equipment. The system is administrated by the Swedish Board of Housing, Building and Planning and the County Government Boards.

So far money has been granted for actions at 227 waterworks according to Table 6. The installations of the aeration equipment and systems are still under way. Therefore the evaluation of the radon reduction efficiencies attained by different type and size of equipment and installations cannot yet be made, but in the near future it will be possible.

Table 5. Rn reduction (%) attained by various aerators in 13 Swedish waterworks.

Waterworks	Aerator	Rn concentration (Bq/l) Raw water	Treated water	Rn reduction %
Gullmarstrand	Packed tower aerator	4 000	40	99
Oxhalsö	”	3 000	50	98
Lillhärdal	”	3 000	50	98
Södra Gräs	Libradon aerator	1 620	75	95
Norra Gräs	”	600	15	98
Skoga	”	3 700	20	99
Örebro	Radon-X aerator	2 400	50	98
Blidö	”	2 800	90	97
Bräcke	”	2 410	50	98
Valdemarsvik	”	2 500	50	98
Siljansnäs	”	1 750	50	97
Nora	”	1 400	70	95
Nora	”	830	15	99

Table 6. Financial support for radon reduction at communal waterworks in Sweden.

Radon conc. in raw water Bq/l	Size of waterworks *	Number of waterworks
100 - 490	S	32
	M	105
	L	36
500 - 990	S	4
	M	22
	L	10
≥ 1000	S	2
	M	11
	L	5

*) S = Small: 1-9 users connected
M = Medium: 10 - 99 - “ -
L = Large: ≥100 - “ -

3.2.1. The study trip to five Swedish waterworks

Two participants from STUK and one from VAR and SSI participated in the study trip in June 1998. They visited five small waterworks, two companies selling various types of aerators and one company producing aerators.

The five waterworks, which had been selected for the visit, produce treated water to some tens of households. Thus commercial aerators could be applied for radon removal. Except a Czech packed tower aerator, that was used in one waterworks, all other aerators were made in Sweden. The results on radon removal efficiencies are shown in Table 7, the photos on the various aeration equipment and the short descriptions on the waterworks are presented below.

Table 7. Data from the five Swedish waterworks visited during the study trip.

Waterworks/ commune	Aerator type	Other water treatment methods	Water throughput m³/d	Rn in water Raw Bq/l	Rn in water Treated Bq/l	Radon Reduction %
Grinduga/ Furuvik	Radonfällan aerator, type RF 150/210	Fe-removal with two cation exchangers	13	2500	90	96
Gagnef	Gasstripper, a Czech packed tower aerator	No other water treatment	40	1300	90	93
Sjugare/ Leksand	Radonett aerator, Ejector+diffused air bubbling	- " -	25	400	<50	>88
Kråkbodarna/ Leksand	Two Libradon aerators	- " -		4000	92	98
Mons Samf./ Siljansnäs	Radon-X aerator, type magnum, spray aeration	- " -	8	1750	50	97

In the **Grinduga** waterworks in a small village of Furuvik Radonfällan aerator (Fig. 4) is used for removing radon from water. Treated water is used in about 50 households. The aerator is made by Gävle Galvan Tryckkärl AB. This type of the aerator contains a cyclone reactor, where air enters turbulently to the water stream with help of vacuum valve by low pressure. The pressure is caused by a reduction of the flow diameter. Turbulent mixture of air and water is flowing to the galvanised aerator tank through the special ejector which is called a cyclone reactor. With the help of pressure loading pump water is circulated through to the cyclone reactor several times and then passed for the consumption through the pressure tank. In the **Grinduga** waterworks there are two automatically controlled cation exchangers for removing iron from water. The cation exchangers are installed before the aerator device.

Figure 4. The Radonfällan aerator (left) and the two cation exchangers (right) in the Grinduga waterworks in Furuvik.

Figure 5. The Gagnef waterworks, where a Czech packed tower aerator is applied for radon removal. A pressure tank is located on the left, the inlet air duct (in the right) is equipped with a channel blower, which helps the incoming air to flow downwards through the air filter (inside the upper part of the duct) and then upwards in the narrow packed column located in the middle.

Figure 6. The Radonett aerator is applied for radon removal in the Sjugare waterworks in Leksand.

Figure 7. Two Libradon aerators (on the left) are utilised for radon removal in the Kråkbodarna waterworks in Leksand. A pressure tank is located on the right.

In the waterworks of **Gagnef** radon is removed by using a packed tower aeration unit (Fig. 5). The equipment has been installed by Kemidepån and model of aerator is SK20. It is a narrow model and the height of the tower is 190 cm. The waterworks produces treated water for 25-30 households.

Before the water is sprayed to the aerator, it is flown through the 3-way valve which allows water to bypass the aerator device when needed. Water flows in the packed column downwards, while air is blown upwards. The incoming air is filtered by a filter located inside the upper part of the air inlet duct. The air is blown to the aerator by using a channel blower. Radon-rich air is exhausted to the outdoor air from the top of the packed column through the ventilation duct.

The well pump is controlled by the level switch of the aerator. Treated water is pumped from the bottom of the aerator with pressure loading pump through the pressure tank for the consumption. The pressure switch controls the pressure loading pump.

A Radonett aeration equipment (Fig. 6) from the Sarholms Plåtdetaljer AB company in Rättvik is applied for radon removal in the **Sjugare** waterworks in Leksand. In this aerator air is applied to the water stream with the help of ejectors. Mixture of air and water is then sprayed to the tank. With a pressure loading pump water is circulated through the ejectors several times. This stainless steel device contains two circulation lines. Finally water flows into the water basin (under the waterworks) and from where for the consumption through the pressure tank. The well pump is controlled by level switch of the basin and the pressure loading pump at the bottom of basin is controlled by pressure switch.

In the **Kråkbodarna** waterworks in Leksand**,** radon is removed with two Libradon aerators (Fig. 7) produced by the Libradon AB company. Normally only one aerator is used, but in the summer time the both aerators might be needed due to the increased water consumption in the summer houses.

The well pump pumps raw water to the aerator through an ejector. Mixture of air and water is directed under the water surface. A pressure loading pump, locating inside the aeration tank, is circulating water through the ejector several times. Circulating time can be adjusted from zero to tens of minutes. Aerator tank is made from grey coloured, PVC-plastic; its diameter is 42 cm and height 95 cm. Water volume of this unit is 60 litres. The treated water flows from the aerator to the consumption through the pressure tank.

In the **Mons Samf.** waterworks in Siljansnäs radon is removed with a RADON-X magnum aerator (Fig. 8) produced by Eko-teknik. This aerator is based on spray aeration and on the water circulation in the aeration tank. This waterworks produces treated water for 21 households.

Raw water is sprayed into an aeration tank(made from PE-plastic) through a flat spraying nozzle. After the tank is filled with water, the circulation of water takes place through two other, flat nozzles. A pressure loading pump (located above the aeration tank) pumps the aerated water for the consumption through the pressure tank.

Figure 8. In the **Mons Samf.** waterworks in Siljansnäs radon is removed with a RADON-X magnum aerator equipped a plastic aeration tank. The water level is easily visible due the dark colour on the inner surface of the tank. The colour is probably caused by the precipitated manganese hydroxide. No manganese removal is however needed due to its low content in water. The radon rich air is exhausted to the outdoor air through the ventilation duct, which has just been opened in the figure.

The participants were very content for this study trip, to see how a group of houses had organised their water supply together in various villages, and that the aeration equipment originally designed for radon removal in a private home could be applied also in the case of higher water demand. The results on these small waterworks indicate that commercial aerators were efficient enough, when the radon levels are between 1 000 - 3 000 Bq/l and water throughputs 10- 30 m^3 per day. It can be expected that even higher radon levels can be reduced by these equipment, especially with the packed tower aerator, from which also bigger models are available on the market. Corresponding results have also been reported from other Swedish waterworks (Table 5).

3.3. Results from German waterworks, where conventional water treatment methods are applied

The radon removal efficiency of different treatment methods or treatment steps was calculated by measuring radon contents of inflow (raw) and outflow (treated) water (Table 8). In most cases several measurements were made during 1997 and 1998.

Table 8. Radon removal by conventional water treatment in German waterworks.

Water work	Water source	Treatment method	Radon in raw water, average, Bq/l	Radon reduction %
Schwarzenberg	gallery	Closed lime filtration	140	5-10
Annaberg-B.	gallery	Deacidification (NaOH addition)	1100	<5
Annaberg-B.	2 springs	Closed lime filtration	60/150	<10
Glauchau	gallery	Cross-flow aeration	130	>98
Marktleuthen	well	Closed lime and quartz filtration	1300	8
Marktleuthen	well	Closed lime filtration	910	14
Marktleuthen	spring	Open lime filtration	300	4
Kirchenlamitz	3 springs	Open lime filtration	300/700/1000	<20
Kirchenlamitz	well	Closed lime filtration	120	0
Bad Münster	2 wells	Closed iron/manganese removal	350/400	0-25
Bad Kreuznach	2 wells	Venturi aeration	200/300	70-80

3.3.1 Radon removal by Venturi and cross-flow aeration equipment installed in waterworks

3.3.1.1 Venturi aeration

In a waterworks of Bad Kreuznach (water consumption 700 m^3/d) a Venturi water aeration device is installed as a first treatment step to remove carbon dioxide and radon (300 Bq/l in raw water) and to add oxygen. At Venturi aeration (Figure 9) air turbulently enters the water stream through nozzles by low pressure. The low pressure is caused by a reduction of the flow diameter. During the falling distance behind the device (2 m) a turbulent mixture of air and water is created and thus an effective transfer of dissolved gases from the liquid to the gaseous phase takes place.

The aeration takes place in the container room of the Bad Kreuznach waterworks at a water throughput of approximately 30 m^3/h. The radon reduction was determined several times during 1997 and 1998 with an efficiency of 70 to 80 %. As a result of the transfer of radon from water to air a strong enrichment of radon in the indoor air occurs. To gain a rapid air exchange inside the room ventilation openings were installed in the outer walls. Through those openings fresh air replaces the indoor air continually. Nevertheless the radon concentration in the container room air was found to be very high. During a four-day measurement the average was 62 kBq/m^3 with a minimum of 16 kBq/m^3 and a maximum of 99 kBq/m^3.

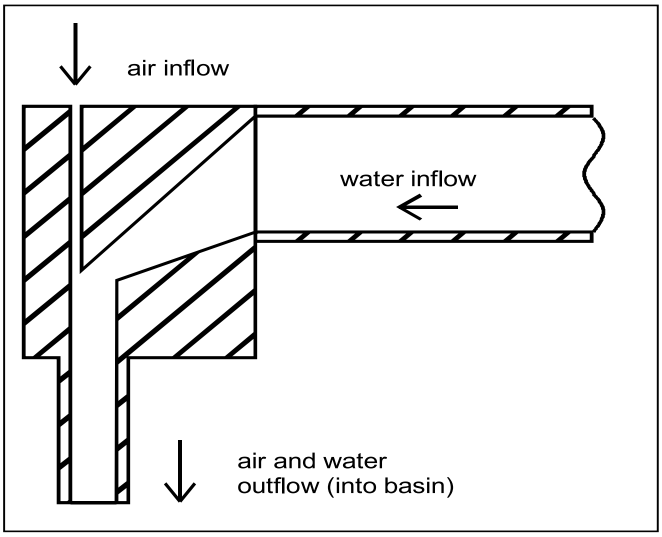

Figure 9. Scheme of Venturi aeration equipment.

The remaining part of the waterworks is separated from the container room by a sealed door to keep the indoor air radon concentration there lower than in the container room. Average values from several long-term measurements were 1 to 3 kBq/m^3.

3.3.1.2 Cross-flow aeration

In a waterworks of Glauchau (water consumption 1 200 m^3/d) a flat-bed cross-flow aeration equipment (Figure 10) is installed as first treatment step to remove carbon dioxide and radon (130 Bq/l in the raw water) and to add oxygen. The size of the equipment is 6 x 2 x 0,8 m. It is operated at a throughput of approximately 50 m^3/h (flux 3 m^3 m^{-2} h^{-1}) and an air/water ratio of 16. Water passes through the equipment on a slightly inclined bed while air is blown through many small nozzles set into the bed in cross-flow direction (see Figure 10). During that process a high percentage of the dissolved gas is transferred from the liquid to the gaseous phase. To avoid radon and carbon dioxide enrichment in the indoor air of the waterworks the used air is transferred outside the building by a ventilation chimney.

During the aeration process almost all radon is removed from water. At several measurements the calculated efficiency was above 98%. Although radon is removed efficiently from water, the indoor radon concentration is quite low. During a 12-day measurement the average was 500 Bq/m^3.

The data in Table 8 show that only the aeration equipment could remove

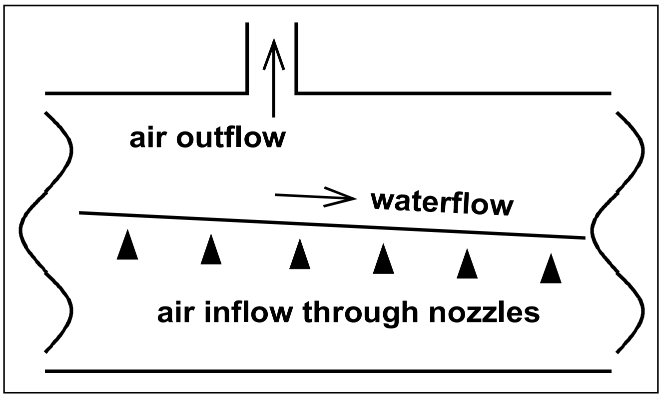

Figure 10. Scheme of flatbed cross-flow aeration equipment.

radon efficiently from water in the German waterworks investigated. Conventional water treatment techniques like iron and manganese removal methods, lime filtration or deacidification were not able to remove more than 25% of the radon.

The Venturi aeration equipment, installed in a waterworks of Bad Kreuznach, removes 70 to 80% of the water dissolved radon. The disadvantage of this equipment is that it produces very high radon concentration in the indoor air . This is because the radon-rich air cannot be transferred directly to outdoor air.

A more suitable method for the radon removal is the flat bed aeration. The equipment (Fig. 10) investigated was able to remove radon gas almost completely. Additionally the radon-rich air can be transferred outside the building without increasing significantly the radon content of the indoor air.

4 Radon removal efficiencies in Finnish waterworks designed for iron, manganese or carbon dioxide removal

Radon removal efficiencies were measured in nine Finnish waterworks, where Fe or Mn removal methods are used (Table 9). Most of these waterworks supply water to certain part of commune, consequently their water treatment capacities vary largely (24 - 5 600m^3/d). The concentrations of radon are quite low (8 - 110 Bq/l) in these waterworks. This is typical to the Finnish waterworks deriving their raw water from aquifers in soil, higher concentrations normally occur only in bedrock aquifers. The results on a few water quality analyses are presented in Table 10. They indicate that the concentrations of Fe vary between <0.07 - 19.6 mg/l and Mn between 0.02 - 0.68 mg/l.

The Fe and Mn removal processes utilised in these waterworks slightly varies from waterworks to another depending on the amounts of Fe or Mn to be removed. They are mainly based on the slow or rapid sand filtration. Aeration is used to oxidise Fe and Mn as hydroxides in all other waterworks except the **Saviaro** waterworks, where chemical oxidising with $KMnO_4$ is necessary due to the high concentrations of Fe (19.6mg/l) and Mn (0.68mg/l) to be removed. Because the alkalinity of water usually decreases during the precipitation of hydroxides, it should be increased by using some neutralising chemical like soda, NaOH or dolomite in order to allow the precipitation and filtration to proceed. The treatment processes in various waterworks are described in brief:

- In the **Heitinkangas** waterworks (in Evijärvi commune) water is first neutralised by lime filtration followed with the gravel filtration. From the gravel filter water flows to the slow sand filtration basin (tree layers; 50 cm of sand, 10 cm of lime and 50 cm of sand) and finally to the storage basin. This waterworks has two separate filtration lines, and in the future the treatment capacity can still be increased because there is also a reservation for a third line.
- The **Onkamo** waterworks is a communal waterworks in Haukipudas commune. Raw water contains Fe (0,2 mg/l) and aggressive CO_2 (pH 6,0) to be removed. Raw water is aerated before slow sand filtration with special dry filter unit. Owing to a relatively low concentration of Fe there is no need to dose any chemicals to the water in the treatment process.
- The **Saviaro** waterworks is another communal waterworks in Haukipudas commune. Maximum water capacity is 2500 m^3/d, but the average daily

consumption about 600 m^3. In order to enable the efficient removal of Fe (19.6mg/l) and Mn (0.68mg/l), NaOH and $KMnO_4$ are dosed to the water before the filtration. A pressure sand filter (height 1,7 m) contains 4 different kind of sand layers (particle size 1,2-4,0 mm).

- The **Vihtari** waterworks in Himanka commune is a communal waterworks. Raw water is pumped from two wells to the cascade gravitation aerator. Water is at first filtered through gravel layer (height 0,5 m) and then through a sand layer. NaOH is added to water before pumping to the storage basin (200 m^3).
- The water consumption in the **Luhanka** waterworks in Luhanka commune is only 24 m^3/d. Aeration unit is pressure tank (2 m^3). Filtration and alkalisation is done in the same basin, which contains two separate layers; a sand layer and a lime stone layer.
- The **Korteskylä** waterworks in Peräseinäjoki commune is a communal waterworks with the treatment capacity of 350 m^3/d. Aeration is carried out by spraying the water through nozzles on the surface of the basin, which has cascade gravitation steps. The slow sand (1 mm) filter basin has an area of 3600 m^2.
- The **Herajoki** waterworks in Riihimäki commune supplies 3500 m^3/d of treated water to a communal network of water pipes. Raw water is pumped from five wells to two packed tower aeration units. Water is spraying to these units through two Dresden nozzles. The packed tower (total height 2,6 m) contains 5 screen (40 x 40 x 3 mm) layers (distance 350 mm). From these aeration units water flows to four sand filter basins. Desinfection solution (NaOCl) is dosed to the water before and after storage basin (700 m^3). Treated water is pumped with four pressure loading pumps for consumption.
- The water consumption of the **Hyhky** waterworks in Tampere is about 2000 m^3/d. Raw water is pumped from three wells to four packed tower aeration units. Total height of the each aerator is 2.4 m, the effective height with fillings of 1.6 m and the surface area of about 5.4 m^2 (total 21.6 m^2). The packed towers are filled with DN 50 pipes (length 200 mm).

Chemicals ($KMnO_4$ and NaOH) are added to water after the aeration using solenoid dosing pumps in order to provide an effective removal of Fe and Mn. The precipitated hydroxides are removed with two rapid sand filters. Each filter has a surface area of 15,1 m^2 and the height the sand layer is 1,2 m. Thus each filter contains 18,1 m^3 sand (0,6-1,2 mm). The sand filters are rinsed with water taken from the storage basin. Air is also applied during the rinsing of the filters.

After rapid sand filters water is disinfected with ammonium chloride solution mixed into water with a static pipe mixer. Thereafter water flows into the storage basin from where treated water is pumped to the consumption with two inverted controlled pressure loading pumps. The Hyhky waterworks is controlled fully automatically from the Rusko waterworks located in the same commune.

- The **Messukylä** waterworks in Tampere commune has built up in 1967. Water aeration is done using cascade gravitation aerator. Chemicals (NaOH and NaOCl) are added to the water before the mixing basin. This waterworks has two separate rapid sand filters.

Table 9 indicates that the radon removal efficiencies vary in a quite large range, between 13 - 91%. It seems that better radon removals are attained if aeration is performed with packed tower aeration or a drip aerator (72 -94%) than by applying spray aeration or cascade gravitation (13-58%). A spray aeration combined with cascade gravitation in the Korteskylä waterworks also seems to remove radon efficiently (81%). Any definite comparisons cannot be made due to the lack of information on various things like the amounts of air (e.g. air/water ratios in packed tower aerators) applied in various aeration processes. Due to the low concentration levels of radon in the waterwork examined here, the measurements should have been performed several times at various dates (possibly in various seasons) to get reliable results. The sampling and analyses errors are also big at these low concentrations levels. It has also been observed during the testing of the domestic radon removal aerators that the removal of the radon residues (tens Bq/l) at the end of the removal process needs more time (air) than the removal in the beginning when the radon levels were much higher (thousands Bq/l). This could partly explain the low removal efficiency attained in the Heitinkangas waterworks.

Table 9. Radon reductions (%) as attained in nine Finnish waterworks, where various types of iron and manganese removal methods are applied.

Waterworks/ commune	Iron and manganese removal method and other water treatment	Aeration method	Water consumption (m^3/d)	Radon in water Raw (Bq/l)	Radon in water Treated (Bq/l)	Radon reduction (%)
Heitinkangas/ Evijärvi	Aeration, lime and gravel filtration, slow sand filtration (sand, lime, sand)	Dresden aerator	210	8	7	13
Onkamo/ Haukipudas	Aeration with mineral wool filtration	Drip aerator	1900	31	2	94
Saviaro/ Haukipudas	Neutralising with NaOH, oxidation with $KMnO_4$, discrete settling, rapid sand filtration	Chemical oxidation	600	38	17	55
Vihtari/ Himanka	Aeration, gravel and sand filtration, neutralising with NaOH	Cascade gravitation	200	16	7	56
Luhanka/ Luhanka	Aeration, slow sand filtration and lime filtration	Packed tower aerator	24	35	3	91
Korteskylä/ Peräseinäjoki	Aeration, sand filtration and neutralising with soda	Spray and cascade gravitation	200	16	3	81
Herajoki/ Riihimäki	Aeration and lime filtration	Packed tower aerator	3500	110	30	72
Hyhky/ Tampere	Aeration, oxidation with $KMnO_4$, neutralising with NaOH, rapid sand filtration	Packed tower aerator	2000	62	7	89
Messukylä/ Tampere	Aeration, neutralising with NaOH, rapid sand filtration	Cascade gravitation	5600	52	22	58

Table 10. Physico-chemical water quality in five Finnish waterworks, where various types of iron and manganese removal methods are applied and from where some water quality parameters have been reported to STUK.

Parameter	Unit	Onkamo / Haukipudas		Saviaro / Haukipudas		Vihtari / Himanka		Hyhky / Tampere		Messukylä / Tampere	
		Raw water	Treated water	Raw water	Treated water	Raw water	Treated water	Raw water	Treated water	Raw water	Treated water
Sampling date		19.5.1998	19.5.1998	19.5.1998	19.5.1998	11.11.1998	11.11.1998	*	*	*	*
Heterot. 35 °C	cfu/ ml	-	-	-	-	-	-	1	0	0	0
Heterot. 22 °C	cfu/ ml	-	-	-	-	-	-	-	3	-	0
Coliformic 35 °C	cfu/ 100ml	0	0	0	0	<1	<1	0	0	0	0
pH		6	6,7	6,5	8	6,5	7,5	6,5	8,1	6,4	7,5
Alkalinity	mmol/l	-	-	-	-	-	-	0,99	1,6	1,2	1,9
Tot.hardness (Ca + Mg)	mmol/l	-	-	-	-	-	-	4,9	4,9	1,1	1,1
Conductivity	mS/m	5,4	5,3	25	30	-	-	25,3	29,8	29,4	36,2
$KMnO_4$	mg/l	-	-	-	-	-	-	2,0	1,6	1,5	1,5
Na	mg/l	-	-	-	-	-	-	11	25	11	29
Fe	mg/l	0,20	0,061	19,6	0,03	0,66	0,05	0,23	<0,06	<0,07	<0,05
Mn	mg/l	0,03	0,021	0,68	0,012	0,02	<0,01	0,10	0,03	0,17	<0,01
NO_3-N	mg/l	-	-	-	-	<0,1	<0,1	1,5	1,5	<0,20	<0,20

* Values are averages of year 1997.

5 Conclusions

Radon measurements were carried out in Finnish, Swedish and German waterworks equipped with different type of treatment techniques as an aim to survey their radon removal capabilities. As a brief summary on these studies following conclusions can be written:

- Diffused bubble aeration combined with the spray aeration was efficient at removing radon in a new waterworks especially designed for radon removal. Diffused bubble aeration and spray aeration alike can be good alternatives to a packed tower aeration especially in waterworks, where they can be combined easily 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 economic than installing a packed tower aerator. The situation is the same when a packed tower is too high to be installed into an existing building.
- Most of various types of packed tower aerators removed radon very efficiently when installed into waterworks or tested in a pilot plant. Even small units applied in a number of waterworks have been efficient enough to supply water to tens of households.
- Various types of commercial aerators originally designed for radon removal in domestic use can be applied efficiently also in small waterworks. This was proved by the results obtained from many installations into different sizes of waterworks.
- The results from those waterworks, which apply aeration in their iron or manganese removal processes, indicate quite often that most of radon has also been removed. If better radon removal is needed,aeration efficiency can often be easily improved. Various aeration alternatives should always be considered in order to save costs.
- Aeration removed radon and carbon dioxide quite similarly. 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 those 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.

6 Acknowledgements

The TENAWA project is carried out on a cost shared basis with CEC under contract No FI4PCT960054 under the supervision of Directorate-General XII Radiation Protection Research Unit. Many discussions have taken place between our colleagues in and beyond the TENAWA project and we gratefully acknowledge these.

7 References

Bünger T, Rühle H. Natürlich radioaktive Stoffe im Trinkwasser ausgewählter Gebiete in Sachsen und Thüringen. In: Winter, M. u. Wicke, A. (Hrsg.): Umweltradioaktivität, Radioökologie, Strahlenwirkungen, 25. Jahrestagung des Fachverbandes für Strahlenschutz, 28.-30.9.1993, FS-93-67-T. Verlag TÜV Rheinland 1993: 85-92.

Hess C.T, Michel J, Horton T.R The occurrence of radioactivity in public water supplies in the United States. Health Physics 1985; 48 (3): 553-586.

Kulich J, Möre H, Swedjemark G.A. Radon och radium i hushållsvatten. SSI-rapport 1988; 88-11: 1-74.

Lonka H, Leveinen J, Tossavainen J. Kalliopohjavesi – Suomen vesihuollon vähän käytetty mahdollisuus (Bedrock groundwater – an option seldom used for water supply in Finland.) Vesitalous (Finnish Journal of water economy, water technology, hydraulic and agricultural engineering and environmental protection)1993; 34 (3): 7-11.(in Finnish)

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

Rühle H. Radioaktivität in verschiedenen Wasservorkommen. In: Siehl, A. Umweltradioaktivität. Ernst. Berlin 1996: 157-178.