Radon removal by aeration: observations on testing, installation and maintenance of domestic treatment units

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ABSTRACT

Radon is one of the contaminants that sometimes impair the water quality of wells, especially those drilled in bedrock. Domestic radon removal units based on aeration have been commercially available for more than ten years. In order to determine how effectively these units remove radon a new test protocol applying frequent sampling while letting 100 litres of water flow, was developed. This way, removal efficiencies can be more accurately calculated and possible malfunctions detected. Seven models of domestic aerators designed for removing radon from household water were tested. The aerators were based on diffused bubble aeration, spray aeration or jet aeration. The average removal efficiencies for 100 litres with a medium flow rate were 86–100% except for a unit that circulated the aerated water back to the well that had removal efficiency of 80% at the maximum. By conducting a questionnaire study usual problems related to the aeration units were localized and recommendations on maintenance and installation are given accordingly.

Key words | aeration, domestic water treatment, radon, sampling

INTRODUCTION

One of the potential contaminants of domestic wells, especially of those drilled in bedrock, is radon. Radon is a radioactive gas that originates from naturally occurring uranium that has been present in the Earth's crust since its formation. Elevated uranium concentrations in bedrock lead generally to high concentration of radon in bedrock wells (Lahermo & Juntunen 1991). Uraniferous rocks are found in many parts of Europe. The highest radon concentrations that have been found in wells drilled in crystalline bedrock of the Fennoscandian shield in Norway, Sweden and Finland have been 31,900, 57,000 and 130,000 Bq/L, respectively (Banks et al. 1998; Mjönes & Åkerblom 1998; STUK 2008). In Central Iberian zone in Spain the highest concentration has been 31,000 Bq/L (Soto et al. 1995) and in Bohemian Massif in Austria and in Czech Republic 758 and 4,000 Bq/L, respectively (Katzberger et al. 2001; Hanslík 2008). The highest radon concentration in well water reported in the US was in New Hampshire, 96,000 Bq/L (Lamarre 1989). Residents using radon bearing water are exposed to radon through ingestion and through inhalation because radon is partly released into indoor air during water usage. This exposure increases mainly the risk of stomach and lung cancer (NRC 1999).

According to the recommendation by European Commission, radon concentration in water from commercial or public water supply plants should not exceed 100 Bq/L but “a level higher than 100 Bq/L may be adopted if national surveys show that this is necessary for implementing a practical radon programme”. Concentration higher than 1,000 Bq/L is not considered acceptable and this concentration is also recommended as the maximum concentration for private water supplies (European Commission 2001).

The first choice for a household that has an elevated radon concentration in their well water is to connect to a water distribution network. These networks, however, are sometimes unavailable owing to long distances to water.
mains from the estate or due to projected low end-point consumption. The only viable alternative in these cases is to remove radon with a domestic water treatment unit.

Research on removing radon from drinking water was started in Czechoslovakia in the 1970s (Hanslik et al. 1978). Aeration was found a suitable method for stripping radon from water. Removal efficiency of 99% was achieved using aeration porous discs with an air-to-water ratio of 8:1 and 8 minutes aeration time. Various aeration techniques and activated carbon adsorption were tested in Sweden in the early 1980s. Aeration under atmospheric pressure was reported to be the best method with removal efficiency up to 75% (Hedberg et al. 1982). Removing radon from potable water was also studied in the US at the same time (Lowry 1983). Three methods were tested and found effective; granular activated carbon (GAC) adsorption, diffused aeration and spray aeration. At first, GAC adsorption was regarded as the most promising method because it was found very effective and it had low investment and maintenance costs. The usability of GAC adsorption was re-evaluated later when it was found that external gamma radiation caused by the units may exceed residential guideline values (Rydell et al. 1989).

Several aeration techniques for removing radon have been introduced including packed tower aeration, diffused bubble aeration, spray aeration, tray aeration, jet aeration, shallow-tray aeration, cascade aeration and pressure aeration in hydrophor (NRC 1999). Domestic aerators designed for removing radon are available from several manufacturers and they conventionally combine jet aeration and spray aeration (Lindén 1997; Mjönes 2000; Vesterbacka et al. 2008). In these applications, water is pumped from the well through a spray nozzle into an aeration tank. A level sensor is used to control the filling of the tank. The water is then circulated by a pump through an ejector that aspirates air into the water until the pre-set aeration time is reached. The water is then directed into a hydrophor applying solenoid valves. The excess air in the tank is ventilated outdoors (Figure 1). Aerators are always installed to treat all household water i.e. point-of-entry because radon is partly released into indoor air during water usage and thus causes exposure through respiration as well.

The objective of this study was firstly to develop a reliable method for evaluating radon removal efficiencies of domestic style aerators. Secondly, the most common problems related to the aeration units were localized by sending a questionnaire to the residents who have radon removal units at home. Ultimately, recommendations on maintenance and installation of the units could be given.

**EXPERIMENTAL**

Seven types of aerators from six manufacturers were tested (Table 1). Radonett from Sarholms Plåtdetaljer Ab is a conventional domestic aerator of hybrid spray/jet aeration type. In this application, the pump that circulates water through the ejector is placed inside the aeration tank, which muffles the noise from the pump. Also, an UV-unit and an air filter are used to prevent microbiological fouling of the aerator. Radon-X100 from HOH Vattenteknik Ab and RF-150 from Oy WatMan Ab are rather similar in structure and match the conventional type of aerator. RnAI-500 from Oy WatMan Ab has a large plastic aeration tank where the pump is also placed. The Vesivahti aerator was originally developed to prevent freezing of the household water pipes and to remove odour and improve taste. It circulates water 5.5 minutes at a time from well to hydrophor and back to the well through two ejectors. The frequency of the 5.5 minute circulation can be adjusted. Radox-aerator from Overcraft Oy is based on diffused bubble aeration where bubbles are created by a hollow, perforated cylinder that is...
rotated by an electric motor. In accordance with Bernoulli’s theorem, a pressure difference is created between the inner and outer surface of the cylinder and air is aspirated into the water as the cylinder rotates. RA 300 from Ins. tst. Vartiainen Oy has a separate air compressor and aeration discs. The last two models, however, are no longer available in the market as of March 2009.

First, a sample of raw water was taken from a separate raw water line. In most cases this was possible because a separate line was installed for usage of water which does not require radon removal e.g. watering the garden or washing the car. In this sampling, about 10 mL of water was let flow in a thin stream directly into a tared liquid scintillation vial pre-filled with 12 mL of liquid scintillation cocktail (Ultima Gold XR from Perkin-Elmer). If sampling of raw water was not possible, radon concentration determined before the installation of the aeration unit was used.

Then, a 25-cm hose was connected to the kitchen tap and the flow rate was adjusted to 4–8 L/min with a stopwatch and a measuring cylinder and the time the flowing started was recorded. Water was let flow into the bottom of a 2 litre flask through the hose and the air bubbles were removed by letting water overflow from the flask. Every two or three minutes a 10 ml water sample for radon measurement was taken with a pipette that was filled by exerting positive water pressure in the bottom of the flask (Kitto 1994). The water sample was then injected into a liquid scintillation vial that was pre-filled with the cocktail. The time of each sampling was recorded. When more than 100 litres of water had flown the sampling was stopped, time recorded and a second sample from the raw water was taken. The radon concentration was determined by counting the samples with Guardian® 1414 from Wallac (Salonen & Hukkanen 1997).

The measured radon concentrations were plotted as a function of the volume of water that had flowed. The removal efficiency for the water sample that was first taken was calculated according to equation:

$$R_0 = \left(1 - \frac{c_{a0}}{c_{r0}}\right) \times 100\%$$  \hspace{1cm} (1)

where $R_0$ is the initial removal efficiency, $c_{a0}$ is the radon concentration in the first aerated water sample, and $c_{r0}$ is the concentration in first raw water sample.

The average radon removal efficiency for 100 litres was calculated according to equation:

$$R_{100} = \frac{\sum n [c_n + c_{n+1})(V_n - V_{n-1})]}{(c_{r0} + c_{rf}) V_{tot}}$$  \hspace{1cm} (2)

where $V_n$ is the volume of water flowed when sample $n$ was taken and $c_n$ is the radon concentration of this sample. $c_{rf}$ is the radon concentrations in the final raw water sample and $V_{tot}$ is the volume at the last sampling i.e. 100 litres. The minimum removal efficiency during the sampling run was calculated according to:

$$R_{\min} = 1 - \frac{2c_{a,max}}{c_{r0} + c_{rf}} \times 100\%$$  \hspace{1cm} (3)

where $c_{a,max}$ is the highest radon concentration measured in the treated water.

In order to gather experiences of the end-users, a questionnaire was sent to 192 households who had purchased equipment to remove natural radionuclides.

### Table 1 | Domestic aerators that were tested

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Brand/model</th>
<th>Aeration type</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sarholms Plåtdetaljer Ab</td>
<td>Radonett B2</td>
<td>Spray/jet</td>
<td>Tank 801</td>
</tr>
<tr>
<td>HOH Vattenteknik Ab</td>
<td>Radon X100</td>
<td>Spray/jet</td>
<td>Tank 2101</td>
</tr>
<tr>
<td>Oy WatMan Ab</td>
<td>RF-150</td>
<td>Spray/jet</td>
<td>Tank 1501</td>
</tr>
<tr>
<td>Oy WatMan Ab</td>
<td>RnAI-500</td>
<td>Spray/jet</td>
<td>Tank 5001</td>
</tr>
<tr>
<td>Ins. tst. Vartiainen Oy</td>
<td>RA 300°</td>
<td>Spray/diffused bubble</td>
<td>Tank 3001</td>
</tr>
<tr>
<td>Overcraft Oy</td>
<td>Radox°</td>
<td>Diffused bubble</td>
<td>Tank 3001</td>
</tr>
<tr>
<td>Sednove Oy</td>
<td>Vesivahti</td>
<td>Jet</td>
<td>Well aeration</td>
</tr>
</tbody>
</table>

*No longer available.*
The questions concerning aeration units were: specifications of the unit, commissioning date, means of storage of aerated water, possibility to by-pass the unit, location of the unit, data on the room where the unit is placed (floor drain, window, water-proof materials, room temperature and ventilation cannel assembly), subjective experience on the noise from the unit, maintenance that has been carried out and malfunctions that may have occurred.

RESULTS

Figure 2 presents the radon concentration in treated water attained by the tested aerators. Normally, radon concentration in the treated water does not remain constant but can vary greatly depending on how much water is used. In many cases aerators are designed to be able to produce water also during high consumption and hence insufficiently aerated water may enter the household water lines. Among the tested aerators, only Radox produced water that had constant radon concentration. This is due to the large storage tank where aerated water was directed after aeration.

The best removal efficiencies (Table 2) were attained by Radonet B2, RnAI-500 and Radox all of which were able to remove nearly 100% of radon from 100 litres of water. Radon-X100 and RA 300 showed slightly lower removal efficiency and concentrations exceeding 1,000 Bq/L were recorded for both. Before testing RA 300, the residents had been using a lot of water and therefore, there was insufficiently aerated water in the plumbing and the first sample had an unacceptably high radon concentration.

Radon-X and Radonet have also been evaluated by Lindén (1997). According to the measurements where only two samples of aerated water were taken, the removal efficiency of Radon-X and Radonet were 95–98% and 99–99.9%, respectively. For Radonet, the results between the two studies are similar but for Radon-X removal efficiency presented here is smaller. The model tested by Lindén was Radon-X and in this study Radon-X100, which is probably an updated model.

Similar test runs were carried out at additional locations and repeated at the first test sites. This sort of sampling was able to reveal malfunctioning better than taking a single water sample. In Figure 3, the test run for RF-150 carried
out with a flow rate 4.5 L/min and 10 minutes aeration time showed 95% removal efficiency for 100 litres and 82% for minimum removal efficiency. A previous test run with 10 L/min and 10 minutes aeration time had shown 99% removal efficiency for 100 litres at this site. As can be seen on the figure, the radon concentration increases rapidly after 90 litres has flown, which indicated that during the fill-up of the aeration tank, untreated water enters the plumbing. The reason was a broken gasket in the solenoid valve. In the same figure, a test run performed on a revamped RA 300 is shown. Since the removal efficiency of the unit was not satisfactory, a second aeration disk was placed whereby the removal efficiency for 100 litres improved to 99%.

Vesivalhti aerator was studied with well water that had shown rather stable radon concentration at three sampling carried out over four months (10,200–11,600 Bq/L). The well was 120 meters deep with a diameter of 125 mm and the pump was located 100 meters deep. First, the 5.5 minutes circulation was adjusted to take place every 45 minutes. After a few days of operation radon samples were taken. Then, the circulation frequency was adjusted to 22.5 minutes and new sampling was carried out a few days later. Radon concentrations at the first and the second sampling were 4,000 Bq/L and 2,500 Bq/L, respectively (Figure 4). Since aeration follows the first-order rate law, we can estimate that in this well, the radon concentration cannot be reduced to smaller than about 2,000 Bq/L with this unit. Radon is constantly transported to the well by ground water flow-trough and from radium-226 that decays into radon. The removal efficiency of this technique depends, thus, greatly on the ground water dynamics of an individual well and therefore sufficient removal efficiencies cannot be assured based on these tests.

The questionnaire was answered by 70 households of which 41 removed radon by granular activated carbon filtration and 17 by aeration. Ten of the respondents reported malfunctions or troubles in their aeration units. Together with those encountered during our tests the most common troubles emerge from the solenoid valves—they had seized up by particles in water, once a gasket was broken and once the coil was burnt. In some cases radon removal efficiency was not sufficient due to a malfunction or increased radon concentration in raw water. At one location, a level sensor had failed which caused overflow and water damage in the room. The piping joints has also leaked and damaged the floor materials. Sometimes the aerator was very inconveniently placed so that cleaning was very difficult and the taps for by-passing the unit could not be conveniently reached. The circulation pumps had caused obtrusive noise, especially if the aeration started in the middle of the night after e.g. someone flushing the toilet. In some cases, water production rate of the aerator was not sufficient and breaks occurred during high water consumption e.g. showering. The cold climate in Finland had also caused problems.
in one case a water pipe had frozen and in another case the exhaust air vent had collected ice and finally gotten blocked. This was caused by the condensed and frozen water vapour in the exhaust vent. Every third of the respondents did not have a possibility to by-pass the aeration unit.

DISCUSSION

This new test protocol gives a much better overview on the functioning and efficiency of the aerator than merely taking a single sample from treated water. Household water usage is not evenly distributed during the day; on the contrary, water usage peaks in the mornings and evenings which now can be better emulated and removal efficiencies calculated accordingly. Newly designed testing has also helped to identify malfunction of the units e.g. the jamming of the solenoid valves.

The type and model of aerator should be selected according to the required water production rate and radon concentration in the raw water. Factors affecting the aerators water production rate are the aeration time and the volumes of the aeration tank and the hydrophor(s). Longer aeration times are needed to reduce higher concentrations of radon and the aeration time should be adjusted so that a sufficient reduction is achieved and no breaks in water supply occur. However, it should be noted that the radon concentration of the raw water may vary significantly (at one of our test locations radon concentration in raw water varied from 3,900 to 15,000 Bq/L) and hence aeration time should be adjusted to achieve sufficient reduction even when the radon concentration in raw water is at its maximum level. The effective volume of the pressure tank should be large enough to enable sufficient water feed into the plumbing during aeration. If the aeration time is 7 minutes and the flow rate from the taps is 18 L/min, there should be a 126-litre effective volume in the tank during the aeration which corresponds to a 500-litre tank with 1 bar pre-pressure.

A possibility to by-pass the aerator should always be considered. Large volumes of water that doesn’t have to be treated is often needed e.g. for washing the car or watering the garden. It is also convenient to have a possibility to by-pass the system if there is a failure in the treatment unit since service is not always available the same day.

The most common malfunction of the aerators is the clogging of the solenoid valves. This normally occurs because of particles in the water, but may also take place because of build-up of calcium scale, ferric hydroxide or manganese oxide. These compounds can be formed during the aeration due to the loss of carbon dioxide, rise in the pH value and oxidising conditions. Later they can transfer to the valves. If iron and manganese removal or water softening is needed, the units should be installed before the aerator to protect the valves from clogging. Particles originating from the drilling can be found in well water several months after commissioning the well and again, after the well has been washed. A filter before the aerator will prevent the particles from entering the unit and causing jamming of the valves.

There are also special requirements for the room where the aerator is installed. Some aerators are rather noisy and therefore the aerator should be located far from the bed rooms. Low pitch sounds are difficult to reduce but sometimes a rubber mat under the pump and the aerator helps. The room temperature should be kept low to prevent the water temperature from rising during aeration, and enhancing microbiological growth. The aerator should not be placed under direct sun light because this can enhance growth of biofilms in systems that are not light-proof. The incoming air should be clean of impurities such as dust and pollen. This is especially important for aerators that are not equipped with separate air filters. The room should also be regularly cleaned to keep the air cleaner. The ventilation channel, which leads the radon-bearing air released from the water into outdoor air, should be wide enough and directed to the roof. The air is saturated with water vapour; hence, the outlet has to be designed properly to avoid build-up of ice during winter. Furthermore, there should always be a floor drain to prevent water damage in case joints leak or solenoid valves clog.

REFERENCES


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