Pre-study of the possibilities of using desalinated sea water in nuclear power plants

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**Abstract**

In this work a procedure to solve problems with humus substances entering an ion exchange desalination plant at the nuclear power plant Ringhals, Sweden, was studied. Organic fouling in the resin in the existing desalination plant by humus substances in the municipal water used as raw water is believed to be the main reason for increased conductivity of the makeup water from the ion exchange desalination plant. Sea water, used for main cooling, desalinated by reverse osmosis (RO) was investigated. The technology was tested in a pilot plant during May-July in 2011. Three membranes were tested, two of them designed for sea water use. The permeate from the sea water membranes had a conductivity corresponding to fresh water quality. When installed upstream of a pilot scale deionization unit, water with conductivity corresponding to demanded quality was achieved. The test period included the upcoming summer period which affected the test results by increased biological activities in the feed water. The RO-technology was found to be a suitable technical solution to the humus problems. The cost would be slightly higher then the cost of municipal water. However, a longer test period together with improved pre-filtration is required to determine long-term effects, since the humus substances may still be accumulated in the resins and by time reduce the operation of the ion-exchange desalination plant.

**Keywords:** reverse osmosis, desalination, sea water, nuclear power, humus, organic fouling, ion exchange, conductivity

**Introduction**

Large volumes of water are used in nuclear power plants for cooling and as makeup water in the steam boiler. As main cooling water source, Kattegatt sea water is used at Ringhals while municipal fresh water is desalinated by ion-exchange and used as makeup water. Pure makeup water is essential to ensure low material corrosion in the nuclear power plant systems.

For several years, Ringhals nuclear power plant, located on the Swedish west coast, has experienced problems with the desalination facility, which consists of deep bed ion-exchangers (cation-, weak and strong anion and mixed resin beds). The water used as feed to the ion-exchange plant contains some undissolved organic substances (polysaccharides and humus). These are believed to foul in the anion and mixed resins, causing increased conductivity of the water from the ion exchangers, which is illustrated in figure 1. Normal and required conductivity of the permeate water from the ion-exchanger is 0.07 µS/cm while conductivity values as high
as 0.2-0.4 µS/cm has been observed at Ringhals. Humus substances and fouling of the resins have been identified as the main cause of the high outlet conductivities. These substances are not removed by regular and ordinary regeneration of the ion exchangers. Ringhals has made some improvements in the operation and maintenance of the ion-exchanger equipment. This has however not lead to a final solution. The research and development department then suggested that the municipal water could be replaced by desalinated sea water. The sea water was believed to contain less of fouling humus substances. The aim of this work was to investigate if it would be possible to replace municipal water with sea water. A literature study of current available technologies was made. Thereafter a specific study of techniques suitable for the Ringhals site was studied. A pre-study, using a pilot plant unit for evaluation of the chosen technology was performed. An economical estimation of operational costs for a full scale desalination facility based on the results from the pilot plant was done.

**Theory**

According to the Swedish National Food Administration, drinking water should have a pH from 7.5 to 9.0, and a specific conductivity below 250 µS/cm [1]. The conductivity of the oceans is around 35 000-40 000 µS/cm, which sets high demands on the desalination techniques [2, 3, 4].

Desalination of sea water is common on small islands and in the Middle East-countries [4]. The purpose of the desalination plants in these countries is to create drinking water for the citizens and water for irrigation. The technique commonly used in these countries is MSF, multi stage flash distillation. MSF gives a high NaCl-rejection but demands large amounts of energy in order to work. The technology is based on flashing water into steam in multiple stages; until the required

![Figure 1 Conductivity in the makeup water from the current anion and mixed resin bed at the desalination unit.](image)
desalination grade and purity of the water is reached [4]. In the Scandinavian countries, larger sea desalination plants to produce drinking water are uncommon, which can be explained by the good access to fresh water in these countries [4]. In the countries in the northern parts of the world the RO, reverse osmosis, technique is the most common, which can be explained by a lower salinity combined with high energy-prices. The choice of technique is though always based on the properties of the feed water and the local conditions [5].

Reverse osmosis

The reverse osmosis is based on the phenomenon of osmosis in the water. Naturally water moves from an area of low concentration through a semipermeable barrier (membrane) to an area of higher concentration.

![Figure 2 Reverse osmosis in action](image)

By adding a pressure which reverses the flow direction in the membrane, reverse osmosis is achieved, illustrated in figure 2. The membrane lets through the water molecules but retains most of the salt, creating desalinated water. The membrane often has a NaCl-rejection between 95-99 percent [5, 6, 7].

The most common type of membrane module is the spiral-woundmodule, in which the membrane is rolled around a center tube. Spiral-wound modules are compact with low footprint. This module design was used in the pilot plant.

Shortcomings of RO-plants are fouling and scaling processes. Fouling is accumulation of unwanted material on the membrane surface of which scaling is one type, referring to crystallization of salts [8]. Fouling can be reduced by addition of anti-foulant chemicals and is partly prevented by a “spacer” that cause turbulent flow at the feed side of the membrane. When the fouling results in reduced water quality or flux it is time to clean the membrane in order to remove the fouled material. Cleaning is often made in two steps – by addition of a caustic solution followed by an acid solution. The membrane is then rinsed until normal pH is reached [6].

Properties of the sea

Outside the coast of Ringhals is the Kattegat Sea. This sea water is used as cooling medium in the plant. The salinity of the water is highly affected by the inflows of the less saline water from the Baltic Sea in the south and by high saline water from the Skagerrak Sea in the north. This means that the chemical properties of the Kattegat Sea vary depending on weather and season [9]. Measurements from the late 70’s indicate that the conductivity of Kattegat varies between 30-35 mS/cm.

The sea water used as feed to the RO in the pilot study was the main cooling water, which had passed the steam condensers. After this passage, the temperature had increased by around 10 °C, which is favourable since it reduces the energy requirement and increases the flux compared to lower water temperatures.

Method

The test period was from May 1-July 4 2011. The reverse osmosis technology was tested in a pilot plant. The facility consisted of a sea water open intake with a coarse strainer and a check valve. The water was pumped with a Grundfos suction pump through a pre-filter. Six types of filters were tested; nominal filters with a pore size of 5, 10, 15, 20 and 50 µm and one 10 µm absolute filter. Subsequently the water entered a 1m³ buffer tank from which the feed to the membrane facility was distributed. In the RO-equipment, the water passed a high pressure pump before it entered the membrane module. The permeate was either discharged or...
led to the small ion exchanger module (4 by 1 liter) to simulate the consisting full-scale ion-exchange unit. Part of the concentrate was recycled to the feed inlet and the rest discharged to the sink. The membrane pilot plant included parts for membrane cleaning as well as an anti-foulant tank, which added anti-foulant chemical. Three different membranes were tested, one Filmtec low energy, brackish XLE-membrane, and two KOCH Fluid Systems TFC Spiral 2540-SW-membranes, both suited for sea water but with different thickness of the fibreglass housing. All membrane elements were 40” long with a 28 mil (0.71mm) spacer.

For optimal run some tests were done, i.e. measurements of the conductivity, pre-filter test and silt density index (SDI) test. The SDI test is a simple method to determine the need of pre treatment. It is defined as the time it takes for 0.5 L of feed water to pass a 0.45 µm-filter at 2.1 bar pressure. Thereafter the flow through the filter is continued for either 5, 10 or most common 15 minutes, and the time for 0.5 L to pass is measured again. The SDI-value is defined as:

$$SDI_f = \left[ 1 - \frac{t_f}{t_i} \right] \times 100$$

A general rule is that when SDI<15 <5 there is no need for prefiltration, when SDI is 5 to 10, prefiltration is needed and when SDI>15 several pre-treatment steps are normally needed.

**Result**

As expected the conductivity of the sea water varied during the test period. Higher values were registered closer to the summer. In April/May the conductivity was 27 000 µS/cm, while it in June/July was 31 000 µS/cm.

The amounts of seaweed and algae in the sea water grew during the test period, which caused clogging of the coarse strainer during the second half of the test period. The increased biological activity also appeared in the SDI-values, SDI of 7.1 at the start of the test period and 9.9 at the end. SDI could only be measured in the beginning of the period—thereafter the amounts of sediment was too big to get a result.

The pre-filter had to be changed 3-4 times a week with a medium flow of 4 litres per minute. There was no major difference in life time between the pore sizes. The 10 µm nominal filter had the same life time as the 5 µm nominal filter, around two days. The 10 µm absolute filter lasted approximately one day.

The XLE-membrane was initially tested with a 150 L/h feed, producing 120 L/h concentrate and 30 L/h permeate. The flux was 65.2 L/m²h with a recovery of 20%. The conductivity of the permeate was 200 µS/cm after 49 hours of operation.

The first SW-membrane had a thin housing and was run at the same operation conditions as the XLE-membrane. The fouling potential was tested during a five-days-period, with the aim to determine during which setting the high pressure pump had to operate to maintain frictional pressure drop of 300 mbar.

After 67 h of operation time, the plant reached some operational equilibrium and the ion exchanger was connected to the permeate downstream of the RO. The pressure of the feed to the ion exchangers varied during the test, causing various flow, which caused some scattering for the monitoring of the anion conductivity. As figure 3 shows there was no indication of the problems related to variations in conductivity of the permeate in figure 1.

Observe the scale on the y-axis, adjusted to fit the anion-graph.

![Figure 3 Conductivity in outlet from anion and mixbed ion exchangers](image-url)
The SW-membrane with thicker housing was then evaluated. This type of membrane element is most common in large scale desalination plants. The membrane plant operated at 150 L/h feed, producing 120 L/h concentrate and 30 L/h permeate. The flux was 65.2 L/m²h and of the recovery 20\%. This made it possible to compare the membranes. Initially, the time to reach a frictional pressure drop of 450 mbar was analyzed. The high pressure pump had a pressure at 700 RPM which was calculated to vary between 28-32.5 bar. A pressure difference of 450 mbar was reached after 177 h of operation time. During the time there were no lasting disturbances in the pilot facility and the system was considered in equilibrium after 24 h. The ion exchangers were connected and fed with 27 LPH until saturation was noticed- after around 50 h for the anion resin and 69 h for the mixed bed (figure 4). A constant conductivity of 0.07 \(\mu\text{S/cm}\) was achieved.

When 450 mbar was reached the high pressure pump settings to determine the pressure required to maintain a frictional pressure drop of 450 mbar was investigated. The flux and flows remained the same. During this test period there were frequent disturbances in the feed, resulting in an unstable system. The ion exchangers were connected after the change and were operated with 27 L/h until saturated a second time. The major disturbances are illustrated as peaks in figure 5, while the minor disturbances are indicated as a scattering conductivity after the anion and mixed resin.

![Figure 4 Conductivity from the ion exchangers after the thick SW-membrane](image)

![Figure 5 Anion and mixed resin bed conductivity after the second feed from thick SW-membrane](image)

A comparison between the two SW-membranes is presented in figure 6. The disturbances in feed also influence the salt-retention, but it is clear that the SW-membrane with thick housing had a higher salt retention.

![Figure 6 Comparison of the salt retention for the two SW-membranes](image)

The conductivity and pH of the permeate facility was logged and compared with requirements for Swedish drinking water criteria. In table 1 the parameters possible to measure are compared. The conductivity from the membrane facility was similar while the pH was a bit low.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Swedish drinking water criteria</th>
<th>Measured values third membrane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity ((\mu\text{S/cm}))</td>
<td>&lt;250</td>
<td>120-220</td>
</tr>
<tr>
<td>pH</td>
<td>&gt;7.5 - &lt;9.0</td>
<td>7.0-7.5</td>
</tr>
</tbody>
</table>

An economic estimate was made for a plant producing approximately 500000 \(\text{m}^3\) per year, with a recovery of 50 \%. The recovery is requested in the large scale plant, but was not possible to determine in the pilot plant due to its capacaty. With the modeled large scale sea water desalination facility a operation cost of
4.73 SEK/liter (0.5 €/m³) is estimated. Today, Ringhals pays 3.20 SEK/m³ for the drinking water (May 2011). This shows that seawater could be used for 48% higher than the present price of fresh water to the plant. It includes investment for installation, operation and maintenance of all equipment but exclude costs for additional buildings.

Table 2 Summary of the economical calculation

<table>
<thead>
<tr>
<th>Cost item</th>
<th>Cost kkr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yearly running cost</td>
<td>12 988</td>
</tr>
<tr>
<td>Cost per liter</td>
<td>4.73 SEK/m³</td>
</tr>
</tbody>
</table>

Discussion

As expected, the feed water conductivity (salinity) varied during the test period. This phenomenon affects large scale plants as well, although these are often equipped with digital sensors and control units which regulates the feed and/or pressure automatically depending on the conductivity. The pilot plant did not have an automatic system, and required manual adjustments during the test period. In a large scale unit, such control system is strongly recommended.

The SDI-value increased during the test period and during a year it may vary a lot. A recommendation is to monitor these values during a long period, at least a year. Probably the SDI₃ will decrease during the cold seasons since there is not abounding biological activity in the sea water during winter. The increased SDI had negative effect on the pre-filters, whose efficiency decreased since the amount of small particles increased with time, allowing a higher percent of the total amount of particles to pass the filter. At least in the summer periods when the amount of organic particles is high, an additional pre treatment step is advisable i.e. sand filtration. Referring to the pilot plant, the problem can be partly solved by moving the feed and facility to another location with a less open intake.

The XLE-membrane, had been used during a long period before the test, which limits the possibilities to present clear conclusions about the performance of this membrane. Although a conductivity value corresponding to fresh water was finally observed, the XLE-membrane would probably not be able to generate this value over time in a large scale and cannot be recommended for use. Since the costs for the membranes as such are similar, there is no reason for using the XLE-membranes in the large scale facility.

The first SW-membrane tested generated a stable production of water with conductivity corresponding to fresh water, although near the criteria of 250 µS/cm. As figure 3 and 4 indicate, there were no disturbances in the conductivity of the simulated makeup water production. This indicates that the sea water may not have the type or amount of humus substances that’s causing problems at the desalination units in Ringhals (figure 1).

The second SW-membrane, with the thick housing, produced water of high quality during the whole test period. Although the membrane plant suffered from disturbances in the feed, the conductivity of the produced water was stable and similar to fresh water requirements. This membrane is recommended for Ringhals in a possible large scale plant. However, long term tests are required to predict the lifetime performance and cleaning needs of the membrane. When first connected, the ion exchangers gave a stable production of water with 0.07 µS/cm, the same value as Ringhals requires for makeup water. Results are illustrated in figure 5. The third time the ion exchangers were connected, there was a lot of frequent disturbances, and a clear conclusion from the information in figure 6 is hard to determine. When comparing figure 5 and 6, they seem to be similar if the disturbances had not occurred. Both tests indicated that the anion resin is saturated in around 50 h while the mixed bed lasted for around 65 h. This is in line with the saturation time in the current desalination facility. The figures 3-6 have no indication of presence of organic fouling illustrated in figure 1. There is a possibility that the problem may occur with time and it is recommended that a pilot plant test is
performed during a longer period with varied climate conditions.

For Ringhals, an installation of an RO-plant may be advisable, both from economical, secure and environmental point of view. In the future, the amounts of humus substances in natural water will grow, resulting in increased organic substances problems in lakes, resulting in increased organic substances problems in lakes, resulting in increased organic substances problems in lakes, resulting in increased organic substances problems in lakes, resulting in increased organic substances problems in lakes.

Using part of the main cooling water as additional or complementary source the long term cost may be reduced.

Conclusions

To sum up, the pilot test was considered to be successful. Future pilot or full scale installations should be relocated to reduce the risks for biological problems using another feed connection together with some improved pre filtration steps. This to secure a safe and stable production of makeup water over the entire year.

Further tests are also required to monitor how the varying conductivity (salinity) affects the membrane performance during varying season and weather conditions. Additional annual test should be run with the same type of membranes during the whole test period, monitoring the effects of cleaning and behaviour of a downstream ion-exchange unit.

References


[9] Bernes C (2005), Förändringar under ytan, Naturvårdsverket