Evaluation of Scaling Prevention in Reverse Osmosis Membranes by Anodic Zinc Addition and Magnetic Fields

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

Introduction

South Africa will experience a water crisis in the near future and the supply will not be able to meet the demand. One of the ways to solve this problem is the desalination of brackish water (groundwater). However, during this desalination process, salts can precipitate on the membrane surface, which leads to a decrease in the permeate quality (% salt rejection) and a decrease in flow per unit area of the permeate (flux). This phenomenon is called fouling.

There are four categories of membrane fouling: scale, silt, bacteria and organic material. Scale has locally been found to be the greatest problem associated with groundwater desalination by Reverse Osmosis (RO) due to the occurrence of unwanted particles on the membrane surface that cause the membrane to clog or to be choked. Fortunately, the unwanted salt precipitates and other unwanted material on the membrane surface can be removed by using anti-scaling agents/chemicals.

Objectives

In this research project two types of anti-scaling measures were investigated (in terms of feasibility; optimisation not included), namely anodically-released Zn and magnetic treatment. The overall aim was to compare the RO results obtained after the use of anodic Zn addition and magnetic fields with the results of a commercially available anti-scalant (in this case the one used at the Bitterfontein desalination plant) for the prevention of scaling in RO membranes.

The following were the original objectives:

- Perform a literature survey of the current status of the art in metals addition and the use of magnetic fields for the prevention of scaling in RO membranes.
- Evaluate the efficiency in scale prevention of a number of configurations of magnetic fields in various relations to the membranes and select the best configuration.
- Compare the selected magnetic configuration(s) to anodic Zn addition and a suitable, commercially available anti-scalant chemical.
- Optimise, within the time and budget constraints, the configurations and dosages of the magnetic fields and Zn respectively.
- Compile a concise, integrated Final Report, which includes results from all of the aims above, as well as an indication of the suitability of the use of magnetic fields and/or anodic Zn addition to prevent membrane scaling.

Tasks

The following were the envisaged tasks:

Use of Zn^{2+} ions to prevent scaling

- Design a system that will generate the optimum amount of Zn^{2+} ions required.
- Determine the optimum amount of Zn^{2+} ions needed on the membrane surface to counteract scaling (theoretically).

- Determine the optimum amount of Zn^{2+} ions needed in the feed to counteract scaling (experimentally).
- Test membranes with and without anti-scalant.
- Compare the RO results of a membrane without any anti-scalant treatment to a membrane treated with Zn ions and a membrane treated with commercial phosphonic acid anti-scalant.

Application of a magnetic field to prevent scaling

- Carry out a literature study on the application of a magnetic field to prevent scaling.
- Investigate the application of an alternating current (AC) field perpendicular to a flat-cell membrane as an anti-scaling measure.
- Investigate the application of an AC field perpendicular to a commercial spiral-wrap membrane as an anti-scaling measure.
- Compare the RO performances (rejection and flux) of treated and untreated membranes.

Rationale

The scaling and fouling of RO membranes is the single most important reason for the need for costly replacements of membranes and the steady decline in the production of quality water over time by RO. Many ground water sources, as well as sea water, will be much more accessible for the supply of potable water if a simple and inexpensive scale prevention method can be found to replace the requirement for expensive, commercial, imported anti-scaling chemicals, and solve the problem of scaling.

Methodology

It was proposed that the following methodology be followed:

1. Carry out a literature study of anodic Zn and magnetic fields as they pertain to membrane treatment. (Special attention will be given to the initial laboratory studies on anodic Zn performed by Prof Paul Coetzee, University of Johannesburg.)
2. Use an anodic Zn unit to produce small concentrations of freshly produced Zn ions. Determine its efficiency under laboratory conditions at the Cape Peninsula University of Technology (CPUT), before commencing with evaluations at the Bitterfontein site.
3. Evaluate the use of various configurations of magnetic fields suitable for RO flat sheet and spiral-wrap membranes for anti-scaling. This work should be carried out at the laboratories of the University of Stellenbosch (SU) and CPUT. The best treatments will be further evaluated at the Bitterfontein site.
4. Compare the anti-scaling efficiencies of the anodic Zn and magnetic methods with the efficiency achieved when using a commercial anti-scalant.

Work on the anodic Zn was to be performed at CPUT and the Bitterfontein plant. Work on the magnetic fields was to be carried out at SU and the Ikusasa plant in Somerset West.

Experimental

Use of Zn ions to prevent scaling

Experiments were carried out on laboratory scale and later at the pilot plant at Bitterfontein. Five different electrochemical cell configurations were evaluated for the generation of Zn^{2+} ions:

- Stainless steel (SS) and Zn electrochemical cell.
- Constant flow SS and Zn electrochemical cell.
- Zinc electrochemical cell.
- Constant flow Zn electrochemical cell.
- Zinc electrochemical cell (generation in rapid scale solution).

A pilot plant study was conducted to compare the laboratory data to data generated under pilot plant conditions. The pilot plant comprised three membranes, each of which was subjected to different treatments: the first was subjected to only raw feed, the second was treated with a commercial phosphonic acid anti-scalant and the third with Zn^{2+} ions.

Application of a magnetic field to prevent scaling

Two types of magnetic measurements were carried out. The first used a flat-cell and membrane, where the change in the flux was monitored when a RMS 80 Gauss 50 Hz AC field was applied perpendicular to the membrane, and when it was not. In the second experiment the change in the flow rate was compared between two similar membrane elements, one of which was in an AC field perpendicular to the membrane and the other not. These experiments were carried out using the conventional RO plant that produced RO water from tap water for the Ikusasa complex. This plant was modified to have two similar elements in parallel, exposed to the same pressure and flow rate – one element was in the magnetic field and the other not.

Results

Use of Zn ions to prevent scaling

Zinc ions were generated in raw brackish water and in rapid-scaling solutions. It was found in the laboratory that Zn^{2+} ions in low concentrations (<120 µg/ℓ) can be utilised as a supplement to, or as a potential replacement for, chemical anti-scalants. In the pilot plant, commercial membranes (98% rejection, as specified by the membrane manufacturer) were exposed to natural ground water scaling: one was used as the control, one was exposed to commercial anti-scalant treatment and the other to anti-scalant treatment with Zn^{2+} ions of less than 20 µg/ℓ. The plant was in operation for more than 2 800 operational hours (within specifications for such a system and membranes).

Over a period of about three months the permeate conductivity for all three membranes decreased from 500 to about 100 $µs.cm^{-1}$. The membrane flux of the membrane treated with the commercial anti-scalant stabilised at an average of 33 $ℓ.min^{-1}.m^{-2}$ after 15 weeks. The membrane flux of the Zn^{2+} ions treated membranes decreased from 31 $ℓ.min^{-1}.m^{-2}$ to 29 $ℓ.min^{-1}.m^{-2}$ after 15 weeks. The membrane flux of the untreated feed decreased steeply to 27 $ℓ.min^{-1}.m^{-2}$ over the same period, and continued to decline. The fluxes of the membranes treated with Zn^{2+} ions and with the commercial anti-scalant became similar, whereas the flux of the membrane without any anti-scalant decreased further with time.

Application of a magnetic field to prevent scaling

Our results showed that, unfortunately, the AC field applied perpendicular to the membrane had no effect on preventing scaling.

Conclusions and Recommendations

Zinc(II) ions can be generated in raw brackish water and can potentially be utilised as a supplement or replacement for chemical anti-scalants. In the pilot plant, the use of a commercial anti-scalant for brackish water still gave the best results, but the use of the Zn^{2+} ions warrant further site-specific investigation as promising results were obtained. The use of Zn^{2+} ions can lead to a significant cost saving where the raw water allows its use, in the case of Bitterfontein this saving may be as high as R0.40/kℓ.

As the AC magnetic field applied perpendicular to the membrane had no effect on preventing scaling, it is recommended that no further rapid-fouling solution flat-cell experiments be carried out.

ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS

AC	alternating current
AFM	atomic force microscopy
CCG	constant current generator
CPUT	Cape Peninsula University of Technology
EC	electrical conductivity
EMF	electromagnetic field
MG/ℓ	parts per million
RFS	rapid-fouling solution
RMS	root mean square power
RO	reverse osmosis
RSS	rapid-scaling solution
SS	stainless steel
SU	Stellenbosch University
UJ	University of Johannesburg
WHO	World Health Organisation
Zn	zinc

1 INTRODUCTION AND OBJECTIVES

1.1 Background

South Africa will experience a water crisis in the near future and the supply will not be able to meet the demand. Several areas are already experiencing problems with water scarcity, e.g. the West Coast and (very recently) the south coast of southern Africa. New and improved technologies have to be found to solve this growing problem. One of the ways to solve this problem is the desalination of brackish water (groundwater).

According to Coetzee and Meyer (2002), most natural or ground water contains relatively high concentrations of calcium, sulphate and bicarbonate ions, and these ions end up precipitating out in the form of carbonates, particularly calcium carbonate, and sulphates. Mineral scale deposits can cause major operational problems in water treatment processes, especially in desalination. Desalination is the removal of salts from water to improve its quality – for reuse and potable purposes (depending on the quality) and is mainly used by municipalities and industries. There are four main desalination processes: distillation, reverse osmosis (RO), electrodialysis and ion exchange (Porter, 1990). Among these desalination techniques, RO has become very cost-effective and the efficiency (i.e. rejection of salts and solids) is high. Reverse Osmosis is a pressure-driven membrane separation process; it involves the removal of salt from solution, through a semi-permeable membrane under a pressure that exceeds the osmotic pressure of the feed solution. Reverse Osmosis membranes can remove between 96 and 99% of solids, unwanted organic and inorganic materials.

During this desalination process, however, salts can precipitate on the membrane surface, which +leads to a decrease in the permeate quality (% salt rejection) and a decrease in flow per unit area of the permeate (flux). This phenomenon, called scaling, is one of four categories of membrane fouling: the others being caused by silt, bacteria and organic material. Scale has been found to be the greatest problem associated with ground water desalination by RO due to the occurrence of salt precipitation on the membrane surface that causes the membrane to become clogged or choked.

Fortunately, the unwanted salt precipitates and other unwanted material on the membrane surface can be removed by using anti-scaling agents/chemicals.

1.2 Problem Statement and Motivation

Salt precipitates on a membrane surface can be removed by using anti-scaling agents/chemicals. However, the latter are normally quite expensive. There is therefore a great need to find a suitable, commercially viable supplement or alternative – and one that will not have a detrimental effect on the product water quality. This is very important, in order to ensure more sustainable operation and more cost-effective provision of potable water from local scaling water sources, such as sea water and brackish ground water.

1.3 Aims and Objectives

In this research project two types of anti-scaling measures were investigated (in terms of feasibility; optimisation not included), namely anodically-released Zn^{2+} and magnetic treatment. The overall aim was to compare the RO results obtained after the use of anodic Zn addition and magnetic fields with the results of commercially available anti-scalants in the prevention of scaling in RO membranes.

1.3.1 Original objectives

The following were the original objectives:

- Perform a literature survey of the current status of the art in metals addition and the use of magnetic fields for the prevention of scaling in RO membranes.
- Evaluate the efficiency in scale prevention of a number of configurations of magnetic fields in various relations to the membranes and select the best configuration.
- Compare the selected magnetic configuration(s) to anodic Zn addition and a suitable, commercially available anti-scalant chemical.
- Optimise, within the time and budget constraints, the configurations and dosages of the magnetic fields and Zn, respectively.
- Compile a concise, integrated Final Report, which includes results from all of the aims above, as well as an indication of the suitability of the use of magnetic fields and/or anodic Zn addition to prevent membrane scaling.

1.3.2 Tasks

The following were the envisaged tasks:

1.3.2.1 Use of Zn ions to prevent scaling

- Design a system that will generate the optimum amount of Zn ions required.
- Determine the optimum amount of Zn ions needed on the membrane surface to counteract scaling (theoretically).
- Determine the optimum amount of Zn ions needed in the feed to counteract scaling (experimentally).
- Test membranes with and without anti-scalant.
- Compare the RO results of a membrane without any anti-scalant treatment to a membrane treated with Zn ions and a membrane treated with commercial anti-scalant (preferably the same anti-scalant as is used in existing RO plants).

1.3.2.2 Application of a magnetic field to prevent scaling

- Carry out a literature study on the application of a magnetic field to prevent scaling.
- Investigate the application of an AC field perpendicular to a flat-cell membrane as an anti-scaling measure.
- Investigate the application of an AC field perpendicular to a commercial spiral-wrap membrane as an anti-scaling measure.
- Compare the RO performances (rejection and flux) of treated and untreated membranes.

1.4 Rationale for the Research

The scaling and fouling of RO membranes is the most important reason for the need for costly replacements of membranes and the steady decline in the production of quality water over time from RO membranes. This scaling takes place due to the inevitable concentration of salts experienced on the surface of a membrane during operation (due to the so-called “concentration polarisation”). A number of ground water sources, as well as sea water, will be much more accessible for the supply of potable water if a simple and inexpensive scale prevention method can be found to replace expensive, commercial, imported anti-scaling chemicals, and solve the problem of scaling.

In this research project two types of anti-scaling measures were investigated (in terms of their feasibility, optimisation not included), namely anodically-released Zn and the effect of the magnetic treatment of water.

From previous work performed for the WRC by Prof Paul Coetzee of the University of Johannesburg (UJ) – formerly Rand Afrikaans University – on both the effect of small quantities of anodically-released Zn and the effect of magnetic water treatment, some promising indications arose. It was found that minute quantities of bivalent metals interfered with calcium carbonate scale formation and turned the scale into non-scaling aragonite crystals. Of these metals, Zn proved to function best. In a WRC study on the use of solar distillation units for rural water supply (Goldie *et al.*, 2008), the use of a Zn metal sacrificial anode also produced non-scaling calcium crystals in the still. Although between 1000 and 3000 µg/ℓ zinc chloride are usually required to be effective, results of Prof Coetzee's laboratory studies showed that <50 µg/ℓ of fresh anodically-produced Zn ions could also achieve the same results.

There is much literature available on the topic of the application of magnetic fields for anti-scaling. Most, including two WRC Reports (Coetzee and Haarhoff, 1997; Coetzee and Meyer, 2002), deal with static magnetic fields. Later the focus was on ion core AC magnetic fields. Recent literature describing AC fields is dominated by reports (many by prominent researchers in the field), on the Grahamtek system – in which the magnetic field is parallel to the membrane (*www.grahamtek.com/Research.htm*). However, no references were found reporting the use of an AC field perpendicular to the membranes – and hence it is on this niche area that we focussed in this study.

1.5 Methodology

It was proposed that the following methodology be followed:

- A literature study, including international literature, will be made of anodic Zn and magnetic fields as they pertain to membrane treatment. Special attention will be given to the initial laboratory studies performed by Prof Paul Coetzee (UJ).
- An anodic Zn unit will be used to produce small concentrations of freshly produced Zn ions. The anodic Zn unit will initially be set up in the laboratory and its efficiency determined under laboratory conditions before commencing with pilot plant evaluations.
- A number of configurations of magnetic fields suitable for RO flat sheet and spiral-wrap membranes will be evaluated against other anti-scaling systems in the laboratories of the Stellenbosch University (SU) and the Cape Peninsula University of Technology (CPUT). The best treatments will be further evaluated on pilot scale.
- The anti-scaling efficiencies of the magnetic and anodic Zn methods will be compared to the efficiency of a commercial anti-scalant. Further changes and improvements will also be made to the magnetic and anodic Zn methods where possible. Optimisation is not included.

Work on the anodic Zn was to be performed at CPUT and the Bitterfontein plant, where anti-scalant costs currently contribute to about R0.40/kℓ. Work on the magnetic fields was to be carried out at the SU and the Ikusasa plant in Somerset West.

2 HISTORICAL AND THEORETICAL BACKGROUND

2.1 Reverse Osmosis

Reverse osmosis is a pressure-driven process by which salt is removed from solution, using a semi-permeable membrane. It can remove about 96-99% of solids, unwanted organic and inorganic materials (Porter, 1990).

2.2 Sea Water and Brackish Water Desalination

Sea water with a salt concentration of 35 000 mg/ℓ, has an osmotic pressure of almost 28 bar and this mandates a membrane element with high pressure capabilities (up to 83 bar), to overcome the osmotic pressure. If a RO sea water plant is required to deliver a product water of potable quality (500 mg/ℓ or less), then the membrane element would require a minimum rejection of 98.6% to attain that product quality at 0% recovery (Porter, 1990) .The salinity of brackish water is usually between 2 000 and 10 000 mg/ℓ. The World Health Organisation (WHO) recommendation for potable water is 500 mg/ℓ, so up to 90% of the salt must be removed from these feeds (Baker, 2004). Two important factors that play a role in water desalination are the recovery rate and the rejection.

2.2.1 Recovery rate

The recovery rate can be defined as follows:

$$\text{Recovery rate} = (\text{product flow rate}) \div (\text{feed flow rate}) \qquad [2.1]$$

The concentration factor is given by:

$$\text{Concentration factor} = 1 \div (1 - \text{recovery}) \qquad [2.2]$$

The relationship between the concentration factor and recovery rate is shown in Figure 2.1. Normally, for plants operating below a concentration factor of 2, that is probably 50% recovery, and membrane scaling is not normally a problem. However, most of the brackish water RO plants operate at 80-90% recovery rate (Baker, 2004), where scaling becomes problematic.

2.2.2 Rejection

$$\text{Rejection (\%)} = ((EC_{\text{feed}} - EC_{\text{permeate}}) \times 100) \div EC_{\text{feed}} \qquad [2.3]$$

where: EC is the electrical conductivity.

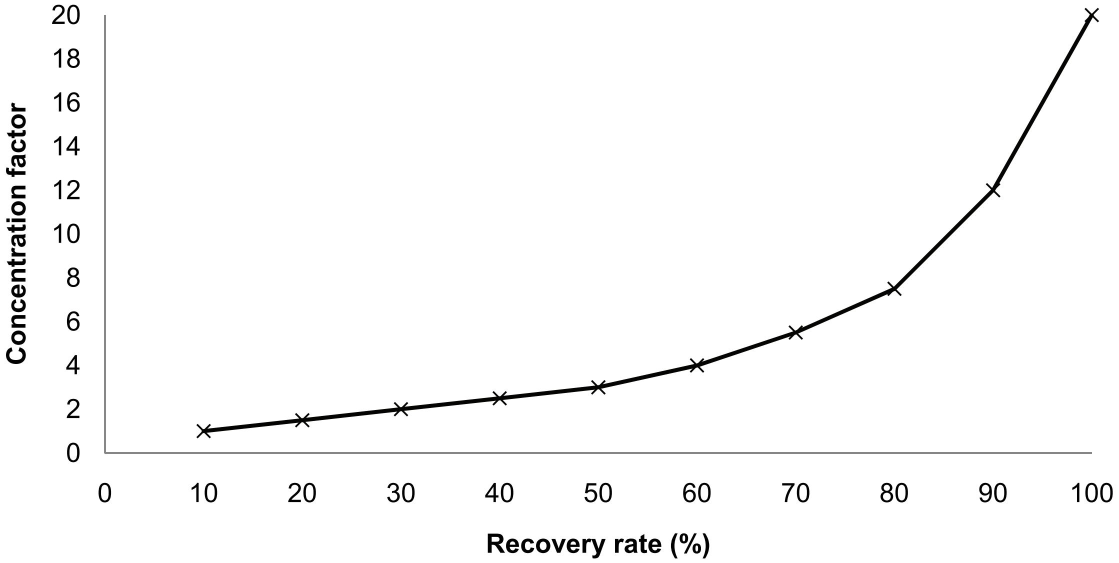

Figure 2.1: Effect of the water recovery rate on the brine solution concentration (Baker, 2004)

2.3 Membrane Fouling

Fouling can be defined as the build-up or the formation of unwanted materials on the membrane surface. Membrane fouling is the main cause of permeate flux decline and loss of product quality in RO systems, so its control frequently dominates RO system design and operation. The type of fouling depends on the type of feed water being treated, and suitable control procedures must be devised for each plant. Fouling can be divided into four categories: scale, silt, bacteria and organic material (Baker, 2004).

Fouling control involves pretreatment of the feed water to minimise fouling as well as regular cleaning to handle any fouling that still occurs. Fouling categories such as silt, bacteria and organic substances (such as oil) can be controlled by applying appropriate pretreatment procedures. This type of fouling tends to affect the primary modules of the plant. Fouling by scaling is however worse, with more concentrated feed solutions, depending on the feed composition and the type of feed water being treated. It is therefore the last modules in the plant that are most affected because they are exposed to the most concentrated feed water (Baker, 2004).

2.4 Membrane Scaling

Membrane scaling can be defined as the occurrence of salt precipitation on the membrane surface causing the membrane to clog or to be choked: scaling strains the membrane and then requires increased use of energy to drive the RO process. This may result in a decrease in the lifespan of the membrane, because of the frequent cleaning required.

During RO, a high conversion is desired, because this will limit the loss of raw materials and energy. Dependent on conversion, about 75-90% of the feed water will be converted to the desired product. During RO, the membrane concentrate absorbs salts, including inorganic salts such as calcium carbonate and barium sulphate, which are water insoluble, and oversaturation can occur. This causes the salts to precipitate. When the conversion to products is high, precipitation of water insoluble salts occurs, which may be detrimental to the membrane. Scaling causes the nominal flux to decrease. The occurrence of scaling subsequently translates into higher costs of water treatment.

2.5 Prevention of Membrane Scaling

Membrane scaling is detrimental but it can be reduced by the use of anti-scalants – surface active materials that interfere with precipitation. This can occur in three different ways (Porcelli and Judd, 2010): threshold inhibition (the ability of an anti-scalant to keep supersaturated solutions of sparingly soluble salts in solution); crystal modification (the property of an anti-scalant to distort crystal shapes, resulting in soft, non-adherent scale); dispersion (the ability of some anti-scalants to adsorb on crystals or colloidal particles and impart a high anionic charge).

Lopez et al. (2007) claim that there is ample evidence in the literature that small amounts of metal ion impurities, notably Zn^{2+}, Cu^{2+}, $Fe^{2+,}$/ Fe^{3+}, and Mg^{2+}, can affect the nucleation and crystallisation rates of precipitating $CaCO_3$ and induce morphological changes of the crystal habit. Zinc ions can significantly hinder calcium carbonate precipitation from hard waters and alter crystal morphology (Lisitsin et al., 2005). It is suggested that Zn ions may precipitate or adsorb on the surface of the crystals and avoid their development. Zinc ions block the crystallisation of calcium carbonate. The effect of Zn on the growth rate of calcite has proved that this element is a good inhibitor because it can reduce the crystal growth rate by 80% for 2 ± 10^{-7} $mol.dm^{-3}$ (Coetzee et al., 1998). Zn^{2+} ions have a very great inhibiting effectiveness for the precipitation in solutions with low concentrations (Wenjun et al., 2008).

2.6 Zinc Ions as Anti-scalant

Some anti-scalants have a negative effect on the environment, and can contribute to water pollution. An advantage of Zn^{2+} ions is that they do not have negative impact on the environment and the water quality is not compromised (it is still suitable for drinking). An upper limit of 5 mg/ℓ Zn^{2+} in drinking water is recommended, not because of a health hazard but due to the astringent taste that Zn^{2+} ions impart to water above the 5 mg/ℓ limit (Lisitsin et al., 2005).

Zinc ions can be generated by means of an electrolytic cell, where filtered water is an electrolyte and the generation is made possible by an electromotive force of the two metals dipped in the solution.

Consider a Zn electrode placed in water: Zn atoms tend to leave the metal and pass through a solution as Zn^{2+} ions. The chemical reaction occurring is: $Zn \rightarrow Zn^{2+} + 2e$

Zinc ions grow in the solution and their valence electrons remain on the metal. The Zn electrodes are negatively charged and the solution is positive. A potential difference between a metal and the solution is established. The positive Zn^{2+} ions are attracted by the negatively charged Zn to reduce the metallic state of the metal, as given by: $Zn^{2+} + 2e^{-} \rightarrow Zn$ (Van Zyl, 2008):

2.7 Application of a Magnetic Field to Reduce Scaling

The literature contains many claims and counter claims about the effect of applying both static and alternating magnetic fields on the surfaces of RO membranes. The WRC has commissioned two studies of the effects of static magnetic fields on scaling.

The first of these, completed in 1997, was entitled ‘Reduction and scaling in industrial water cooling circuits by means of magnetic and electrostatic treatment’ (Coetzee and Haarhoff, 1997). Here a method was developed to verify the effects of the physical water treatment in as short as possible a time, which involved the use of a rapid-fouling solution (RFS). The main conclusion was that (static) magnetic fields did not have an effect on scaling but that the metal ions, especially Zn^{2+}, released into the water being magnetically treated, had a marked effect.

In spite of the negative or inconclusive results of the first study, there was a follow up project entitled ‘Evaluation and development of physical water treatment processes for the reduction of $CaCO_3$ scale’ (Coetzee and Meyer, 2002). Here, effects induced by a static 0.45T magnetic field on scaling, using new analytical technology such as Atomic Force Microscopy (AFM), were studied. Atomic Force Microscopy distance measurements indicated an effect on the electric double layer caused by the magnetic field, but no reduction of the scaling or long-term enhancement of the flux was observed. Due to the lack of success of the above studies (using static magnetic fields), it was decided with the resources and time available, to concentrate on a study of the ability of alternating current (AC) magnetic fields to reduce scaling.

Extensive work using an AC field along the axis of a spiral membrane has been undertaken by Grahamtek Systems (Pty) Ltd. Grahamtek markets systems based on this effect and have carried out a great deal of research in this field (Grahamtek, pers. comm.). In the first system a 50 Hz axial field was obtained by wrapping solenoids along the body of a spiral-wrap element pressure vessel. The current for these solenoids was obtained by running the current from the low voltage side of the pump motor through the solenoids before returning it to the low voltage side of the source. The later systems use higher frequency (2000 Hz) fields. In spite of all this effort not everybody is convinced of the effectiveness of these systems.

A literature search reveals that various parties claim that AC fields alone will “soften” water, and market devices based on this premise. (Note that not all claim the removal of the ions, but only that there is a “softening” of the water.) Considerable research on static magnetic fields has already been conducted in South Africa and elsewhere (Coetzee and Haarhoff, 1997; Coetzee and Meyer, 2002, and references therein). Grahamtek (pers. comm.) has worked extensively on AC fields parallel to the axis. In our research, the focus was therefore on investigating the effect of AC fields applied perpendicular to the membrane.

3 EXPERIMENTAL: INTRODUCTION OF Zn^{2+} IONS

The work was carried out through laboratory and pilot plant studies.

3.1 Preparation of a Rapid-scaling Solution

The following apparatus and reagents were used to prepare a rapid-scaling solution (used throughout): bench scale, spatula, glass sample disc, 500 mℓ cylinder, 6 ℓ flask, $CaCl_2$, $MgSO_4$, $NaHCO_3$. The composition of the solution is tabulated in Table 3.1.

Table 3.1: Composition of rapid-scaling solution used

Salt	Mass per 100 ℓ (g)
$CaCl_2$	61
$MgSO_4$	5
$NaHCO_3$	51

The dry salts were dissolved in 2 ℓ filtered water. The scaling solution was emptied into the feed tank, already containing 98 ℓ of filtered water, with sufficient agitation.

3.2 Commercial Anti-scalant

A phosphonic acid anti-scalant (Vitec 3000, supplied by Avista Technologies) is a commonly used commercial anti-scalant. It inhibits scale and disperses colloidal particles in cellulose acetate and thin-film membrane systems. It is also used in the desalination plant of the West Coast District Municipality at Bitterfontein.

3.3 Measurement of Zn^{2+} Ions in Solution

The following apparatus and reagents were was used to measure the Zn^{2+} ions in solution: Hanna multiparameter ion specific meter (see Figure 3.1), 10 mℓ syringe, 50 mℓ beaker, cuvette with stopper, soft cloth, HI 3854 Zinc Test Kit ('Reagent A', catalogue number HI 3854A-0 and 'Reagent B', catalogue number HI 93731B-0) and cyclohexanone.

The following method was used to measure the Zn^{2+} ions in solution:

A 20 mℓ sample was poured into a beaker, followed by the addition of one packet of Reagent A. The content turned orange. The beaker was slowly swirled until all the solids were dissolved. The multiparameter ion specific meter was switched on and the appropriate program was selected to read Zn ions. (This program is the mechanism that adjusts the appropriate wavelength to read Zn ion concentration.) A 10 mℓ sample was poured into a clean cuvette, which was then covered with a secure stopper and then inserted into the ion specific meter. The validation took a few seconds. The cuvette was then removed and 0.5 mℓ Reagent B was added, using a measuring syringe. The sealed cuvette was reinserted into the meter. A measured concentration was displayed after approximately 3.5 min.

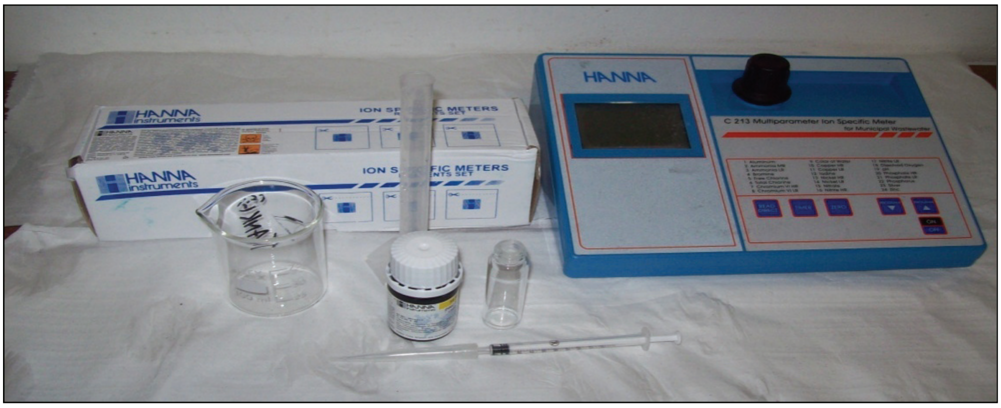

Figure 3.1: Multiparameter ion specific meter

3.4 Design and Operation of the Laboratory Scale RO System and the Application of Anti-Scaling Measures

Experimental configurations of the RO system set-up and the electrochemical cell set-up are described below.

3.4.1 Design

A diagram of the RO system used is shown in Figure 3.2.

3.4.2 Operation

A BW3040-40 Filmtec brackish water membrane with spacer was cut to fit perfectly into the cell of a RO bench scale cell. The membrane was soaked in filtered water for 10 min before utilisation. The membrane cell was closed and sealed with an O-ring to prevent leakages. An average applied pressure of 2500 kPa was applied by an external hydraulic pump. The feed tanks were filled with rapid-scaling solution (RSS). A desktop computer was programmed with a Labview software program to log, control, manipulate and optimise experimental parameters.

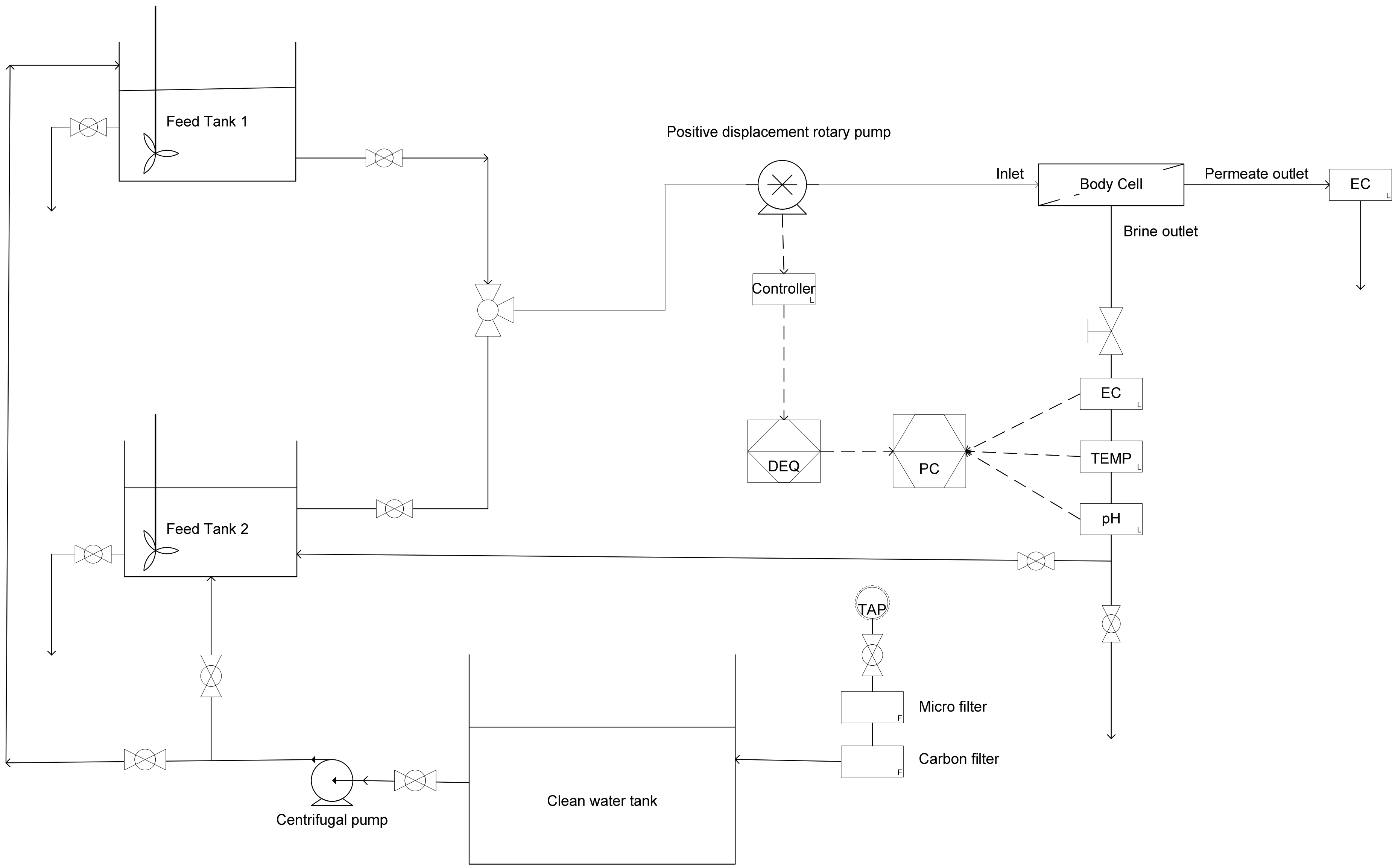

Figure 3.2: Design of the RO membrane system, used for Zn anti-scalant studies
(DEQ: process logic controller)

3.5 Electrochemical cell configuration

The electrochemical cell configurations were of five types:

- Stainless steel (SS) and Zn electrochemical cell
- Constant flow SS and Zn electrochemical cell
- Zn electrochemical cell
- Constant flow Zn electrochemical cell
- Zn electrochemical cell (generation in RSS)

3.5.1 Stainless steel and Zn electrochemical cell

Apparatus:
- 500 mℓ beaker, Zn bar, SS bar, transformer, ammeter, connecting wires, stopwatch.
- Experimental set-up:
- The set-up used here is depicted in Figure 3.3.

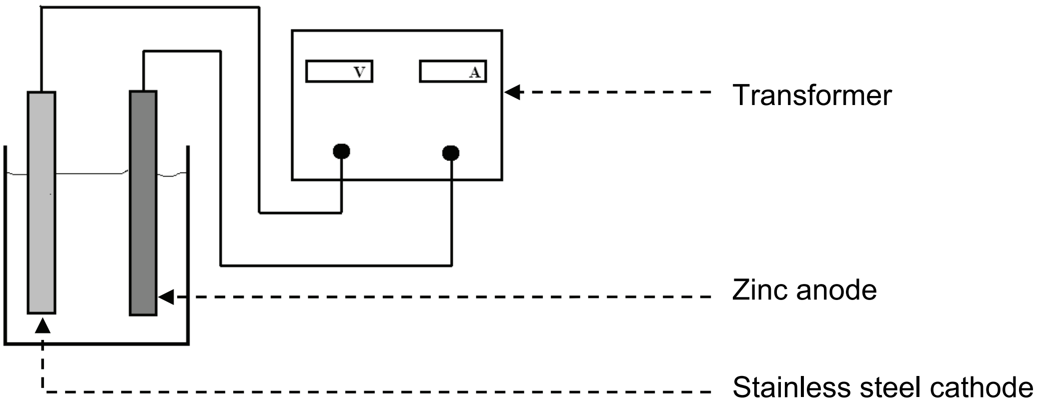

Figure 3.3: Stainless steel and Zn electrochemical cell

Method:
The beaker was filled with 500 mℓ filtered water. The Zn bar (anode) and SS bar (cathode) were then placed into the beaker. The connecting wires were connected between the bars and the transformer. The voltage was then set on the transformer and the stopwatch started. A sample was taken every 10 min and the Zn concentration measured using the procedure described in Section 3.3. The volts, amps and Zn concentration were recorded every 10 min. This experiment was repeated using different voltage settings, in order to determine the optimum point for Zn generation.

3.5.2 Constant flow stainless steel and Zn electrochemical cell

Apparatus:
- As described in Section 3.5.1.
- Experimental set-up:
- The set-up used here is depicted in Figure 3.4.

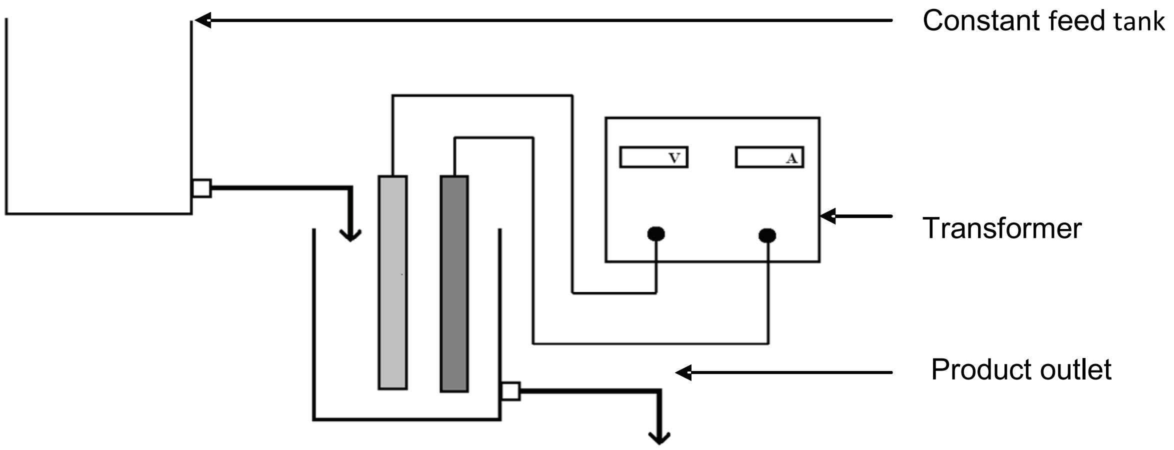

Figure 3.4: Constant flow stainless steel and Zn electrochemical cell

Method:
The two 500 mℓ tanks were connected in series. Tanks 1 and 2 were filled with filtered water. The Zn bar (anode) and SS bar (cathode) were then placed into the second beaker which was to be the electrochemical cell. Next, the connecting wires were connected between the bars and the transformer. The valves were then set to the according flow rates. The function of the constant feed tank is to keep the level constant in tank 2. The voltage was then set on the transformer and the stopwatch started. A sample was taken every 10 min and the Zn concentration measured, using the procedure described in Section 3.3.

3.5.3 Zinc electrochemical cell

Apparatus:

- 500 mℓ beaker, 2 × Zn bars, constant current generator, relay switch, connecting wires, stopwatch.
- Experimental set-up:
- The set-up used here is depicted in Figure 3.5.

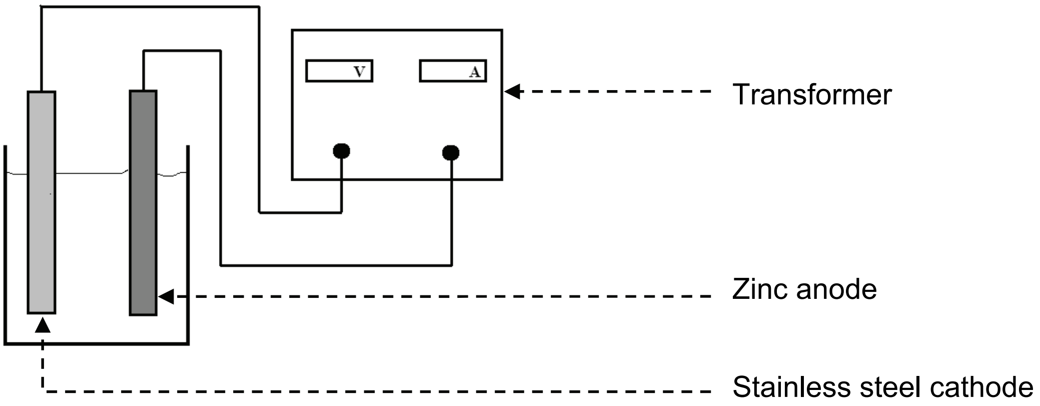

Figure 3.5: Zn electrochemical cell

Method:
The beaker was filled with 500 mℓ filtered water. The Zn bars were placed in the beaker. The connecting wires were connected between the bars, current converter and the transformer. The function of the relay switch is to swap the charges of the electrodes around at a set rate. Thus charge collection was eliminated on the electrodes. The voltage and amps were then set on the constant current generator and the stopwatch started. A sample was taken every 10 min and the Zn concentration measured according to the procedure described in Section 3.3. The voltage, amps and Zn concentration were recorded every 10 min. This experiment was repeated using different volt and amp settings, to determine the optimum point for Zn generation.

3.5.4 Zinc electrochemical cell (generation in rapid-scaling solution)

The same experimental set-up was used as in Section 3.5.3, but instead of using filtered water the RSS was used.

3.5.5 Constant flow Zn electrochemical cell

Apparatus:
Plastic electrochemical housing, two Zn bars, relay switch, dosing pump, connecting wires, stopwatch. The experimental set-up is shown in figure 3.6.

Method:
The dosing pump feed pipe was inserted into real brackish water and the pump started. The flow of water through the electrochemical cell was then calculated. After this the volts and amps were set on the constant current generator and the stopwatch started. A sample was taken every 10 min and the Zn concentration measured according to the procedure described in Section 3.3. The volts, amps, flow rate and Zn concentration were recorded every 10 min. This experiment was repeated by using different volt and amp settings to determine the optimum point for Zn generation.

Experimental set-up:

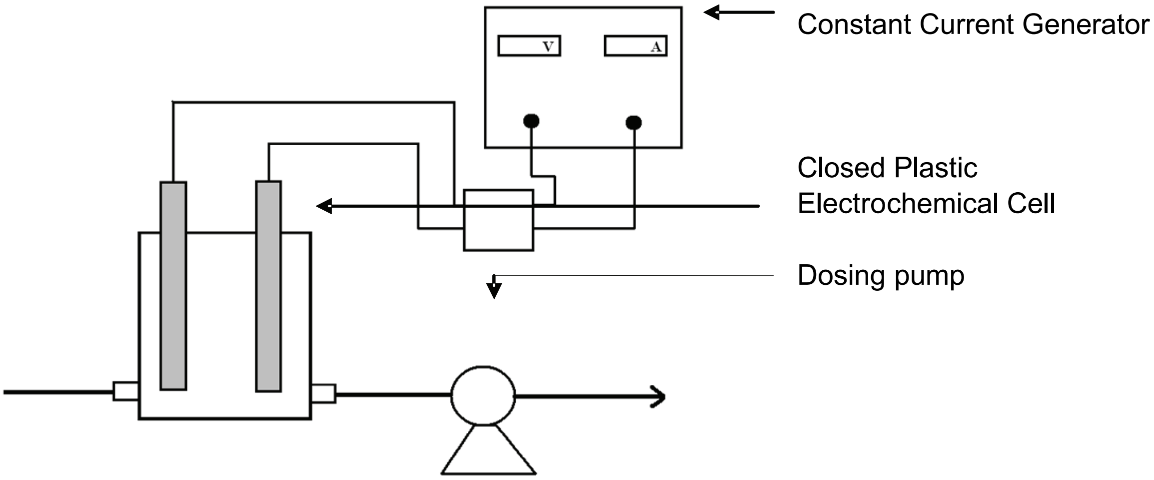

Figure 3.6: Constant flow Zn electrochemical cell

3.6 Procedures

In all cases, for the first hour, fresh clean water was recycled through the RO system in order to achieve stability. The pump RPM, permeate flow rate and electrical conductivity were recorded every 15 min. In all cases, tests were normally run for 5 h, and on completion of tests the membranes were removed.

3.6.1 Rapid-scaling solution with no anti-scalant added

The RSS (prepared as described in Section 3.1.1) was pumped through the system (a non-recycle configuration).

3.6.2 Rapid-scaling solution with anti-scalant added (batch system)

The RSS was prepared as described in Section 3.3.1, but here 0.5 mℓ of the commercial anti-scalant was added to the 100 ℓ tank.

3.6.3 Rapid-scaling solution with anti-scalant added (continuous dosing)

The RSS was pumped through the system with a non-recycle configuration. Commercial anti-scalant was introduced into the feed line to the high-pressure pump. See Figures 3.7 and 3.8.

3.6.4 Rapid-scaling solution with Zn^{2+} ions added (batch system)

The RSS was pumped through the system with a non-recycle configuration. Two Zn electrodes were placed in the solution and left to generate the required amount of Zn^{2+} ions.

3.6.5 Rapid-scaling solution with Zn ions added (continuous dosing)

The RSS was pumped through the system with a non-recycle configuration. Zn ions were introduced into the feed line to the high-pressure pump using the electrochemical cell configuration 3.5.3. See Figures 3.7 and 3.8.

3.7 Pilot Plant Study

A pilot plant study was conducted to compare the laboratory data to data generated under pilot plant conditions. The pilot plant comprised three Dow XLE 4040 membrane modules in parallel: the first was subjected to only raw feed, the second was treated with commercial anti-scalant, and the third was treated with Zn^{2+} ions.

The pilot plant study was conducted at Bitterfontein, which falls under the auspices of the West Coast Municipal District. Raw brackish water was passed through a sedimentary process before entering the pilot plant. The pilot plant data were electronically logged. These readings included the following: feed conductivity, feed flow rate, feed temperature, permeate conductivity, and permeate flow rate. Some readings could not be read by the onboard systems, i.e. potential difference, current, and Zn^{2+} concentration. These values had to be recorded manually by the water works operators at Bitterfonten. The Zn^{2+} concentration was however recorded weekly by a CPUT student (using the procedure described in Section 3.3). The permeate conductivities and permeate flow rates of the respective membranes were then compared with the results recorded on laboratory scale.

Figure 3.9 shows a schematic representation of the pilot plant design and layout. Figure 3.10 shows a photograph of the Ikusasa pilot plant at Bitterfontein.

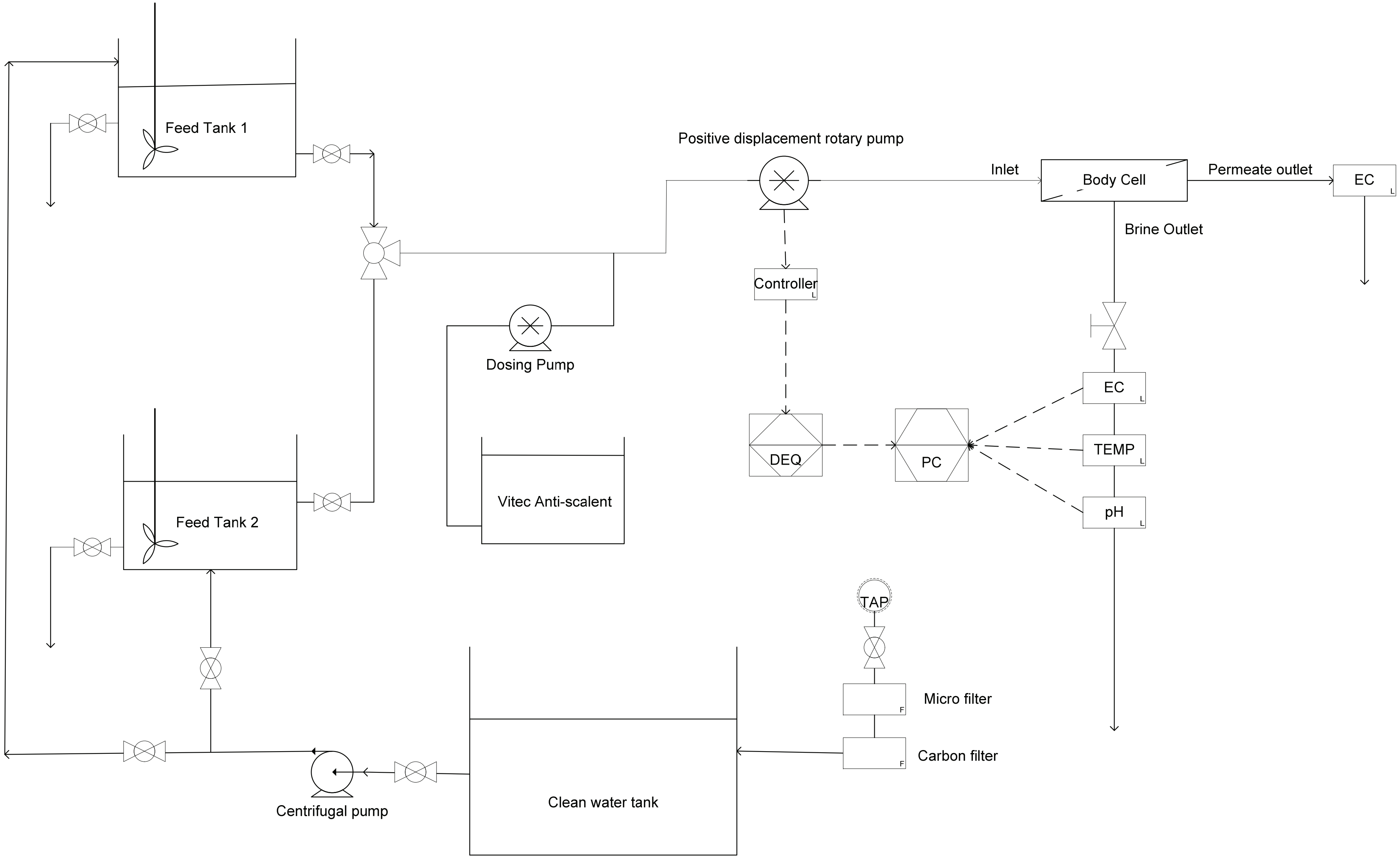

Figure 3.7: RO membrane system, used for investigation of the addition of commercial anti-scalant

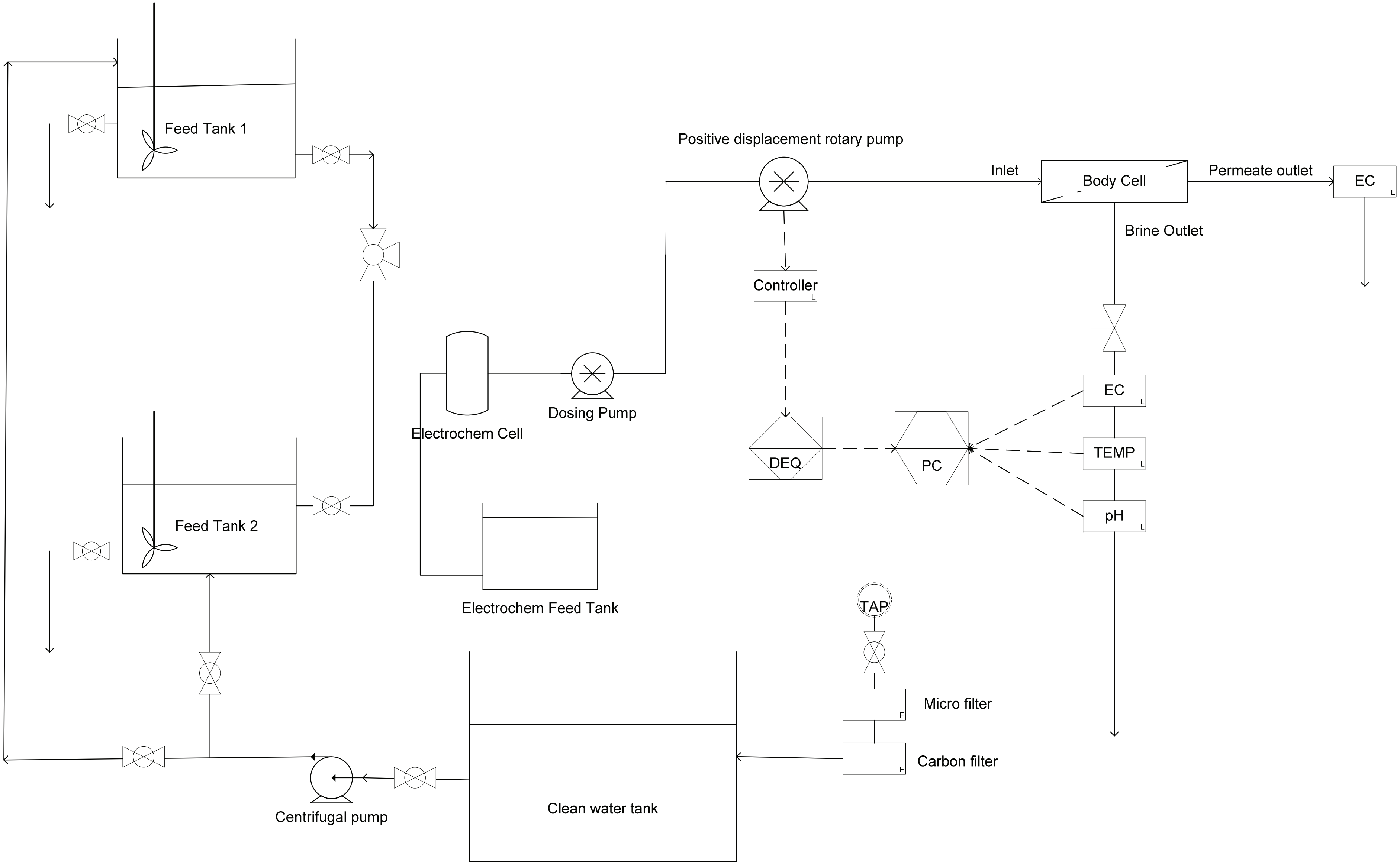

Figure 3.8: RO membrane system with electrochemical cell modification

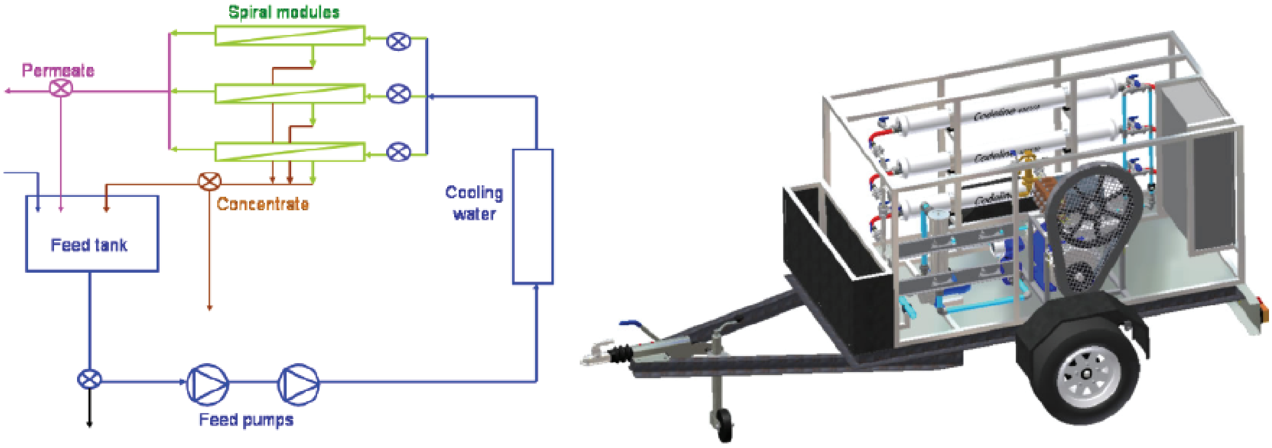

Figure 3.9: Simplified pilot plant design and layout

Figure 3.10: Photograph of the RO pilot plant at Bitterfontein (main plant visible at the back)

4 EXPERIMENTAL: APPLICATION OF A MAGNETIC FIELD

4.1 Introduction

In the following experiments the effect of the electromagnetic field (EMF) and the underlying mechanisms may be understood as follows. The induced electric field alternates sinusoidal 50 times per second. Due to the opposite charges of the anions and cations in the feed solution, they will tend to move in opposite directions. If the ions were not scattered they would flow around circular paths in opposite directions. The axis of these paths would be perpendicular to the membrane. If there is an effect, one could conclude that the continuous movement of the anions and cations in opposite directions interferes with the formation of the concentration polarisation layer at the membrane surface and reduces the formation of calcite crystalline deposits (scale), thereby reducing the overall process of membrane fouling.

4.2 Magnetic Measurements

Two types of magnetic measurements were carried out. The first used a flat-cell and membrane, where the change in the flux was monitored when a RMS 80 Gauss 50 Hz AC field was applied perpendicular to the membrane, and when it was not.

In the second experiment the change in the flow rate was compared between two similar Dow Filmtec XLE-4040 spiral-wrap membrane elements, one of which was in an AC field perpendicular to the membrane and the other not. These experiments were carried out using the conventional RO plant that produced RO water from tap water at the Ikusasa complex. This plant was modified to have two similar elements in parallel, exposed to the same pressure and flow rate – one element was in the magnetic field and the other not.

4.3 Scaling

As the feasibility of this descaling method had to be established fairly quickly, initial trials were performed using a RFS, as used by Lisitsin et al. (2005) in a descaling study. When using this foulant solution, the pH and temperature were important and so had to be kept within the bounds for rapid fouling, as specified. The standard RFS was made up using 22 g $CaCl_2$, 1 g $MnSO_4$ and 14 g $NaHCO_3$ in 100 ℓ RO water.

4.4 Flat-cell Experiments (Laboratory Scale)

4.4.1 Apparatus

A rectangular, flat-bed microfiltration module (100 mm length, 32 mm width and 19 mm height) was used in all the flat-cell experiments. The module was made of polycarbonate and consisted of two plates (each 19 mm thick, 200 mm long and 94 mm wide). The feed space cavity in the top plate (2 mm deep, 88 mm long and 30 mm wide) had three 2 mm inlet pipes at each end which, through separate manifolds, were connected to the input and output feed lines. The membrane rested on a sintered brass plate, set in the lower polycarbonate plate, and below this was another cavity, 13 mm deep, 88 mm long and 30 mm wide, to collect the permeate. The effective membrane area was 0.0032 m^2 (100 mm × 32 mm), which was the area of the brass sintered plate. The membrane was placed on the sintered plate and the two halves were clamped together by a system of 12 nuts and bolts, and sealed with an O-ring.

The membranes used in this work were cut from a small commercial low-pressure brackish water RO element. This was a Filmtec RO element XLE-2521, designed to operate at 6.9 bar, with a maximum salt concentration of 500 mg/ℓ. The membrane was placed about 11 mm above an E core AC field magnet source. A transformer coil consists of an E and an I section which, when placed together (EI), provides a closed magnetic circuit. A single winding was wound around the central section of the E piece, which had a cross section of 55 mm × 45 mm, and the centre of the membrane was placed directly 11 mm above this section. For a current of 1 amp, the field at the centre of the membrane was found to be close to 80 Gauss and to drop to 60 Gauss at the two corners. The vertical gradient at the centre was found to be 0.75/Gauss/mm or 0.75 T/m. The experiments conducted in this part of the project used this E field magnetic configuration.

4.5 Spiral-wrap experiments (at Ikusasa Factory)

4.5.1 Apparatus

The layout of this plant is illustrated in Figure 4.1. The pump used could give a maximum pressure of 50 bar and also had a very high flow rate. Therefore, the pressure and flow rate were controlled using valves 3 and 9. Most of the piping was made from SS, rated at over 50 bar. However, to readily access the cell inside the available magnetic fields, the high pressure SS part of the plant was linked to the cell using 10 bar flexible pipes and very convenient snap-in connections. Therefore, this system limited the testing to low pressure membranes, designed for brackish water.

In this plant the pressure was measured at the input of the cell and the flow rate after the throttling valve (V 9). When running the plant, it was found that the feed pressure tended to oscillate. Therefore to damp this oscillation an 8 bar ballast tank was installed. The presence of the ballast tank meant that it took up to 20 min to adjust the feed flow and pressure to the desired values. Valves V 6, 7 and 8 were not used in these experiments. As shown, a beaker was placed upon an electronic scale to collect the permeate; a computer was connected to the scale and logged the mass as was registered on the scale every 30, 60 or 120 sec. The permeate flow and then the flux were calculated and plotted as a function of time.

The simplest method of achieving this is to use the magnetic field configuration which occurs inside the stator of an AC squirrel cage motor and which causes the rotor to rotate. If one examines the field at any point on the surface of the cylinder symmetrically located inside the motor, a sinusoidal AC field is observed. The RMS value of this field on the cylinder is not constant, but varies around the circumference of the cylinder, being highest under the poles of the stator.

In order to achieve this magnetic field configuration, the stator sections of 5 AC motors, with the same internal cross-section, which had a sufficient internal diameter to accommodate the pressure vessel of the membrane element, were welded together. This 0.8 metre long stator was then wound as a normal motor would be, except that each winding was 1.05 metres long (length of the stator plus the length needed to turn the winding through 180°). The stator covered about ⅔ of the element. The three-phase variable voltage and current, which created the magnetic fields, were obtained from an inverter. A photograph of the stator coil in the RO plant is shown in Figure 4.2.

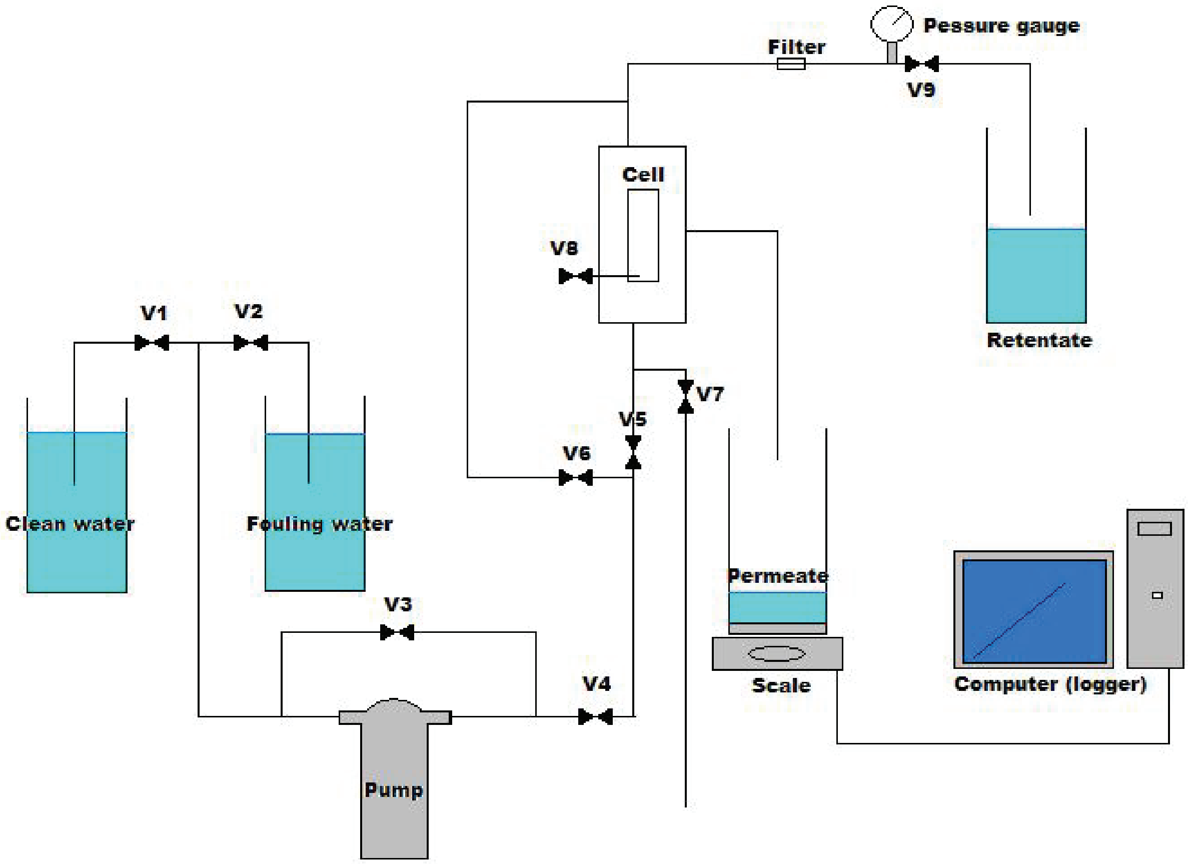

Figure 4.1: Diagram of the layout of the small RO plant used for spiral-wrap experiments

Figure 4.2: Photograph of the stator coil used in the RO plant at Ikusasa factory

The current was set at a low 2 amp, in order to avoid heating in the stator, and the magnetic field was measured using a bell gauss meter close to the surface of the pressure vessel. For this current the RMS fields under the poles peaked at about 50 Gauss and in between it dropped to about 8 Gauss.

Although the tests were originally to be carried out at the Bitterfontein plant, logistics and the availability of skilled manpower lead to the tests being carried out at the Ikusasa premises in Somerset West. An existing RO plant, which produced RO water (using Somerset West tap water), was modified so as to have two elements in parallel, both of which have the same pressure and flow rate. From previous experience the parameters were chosen so that fouling would be observed after a period of about two weeks. Both membrane elements were Filmtec XLE 4040, the pressure was 250 kPa, and the brine flow rate was between 210 and 270 litres per hour. The flow rate from both elements was monitored using a FIPA "rota meter" flow meter.

4.5.2 Procedure

The procedure used for this experiment was very straightforward. The flow rates from both elements (with and without the AC field) were monitored manually and recorded at least twice daily during the working week (but not on weekends). The brine flow rates and other variables were also recorded at these times.

The procedure was to first measure the clean water or RO flow rate for a period of about 30 min. After this RFS was added to the feed tank over a period of about 3 min. The circulation pumps were running and the feed tank was continually stirred. Subsequently, the permeate flow rate was monitored for a further 60 min. This procedure was carried out with and without the AC magnetic field being switched on and the results compared.

5 RESULTS AND DISCUSSION: INTRODUCTION OF ZINC IONS

Note here that the concentration of Zn^{2+} ions generated was fed into the RO feed water system unless stated otherwise.

5.1 Electrochemical Cells (Laboratory Scale)

5.1.1 Stainless steel–Zn electrochemical cell

Results were recorded for the SS–Zn electrochemical cell (Figure 5.1, p. 23). The experiment was repeated for different constant voltage settings, but with unregulated current.

Zinc ions grow in solution and their valence electrons remain on the metal. It is electropositive and has a strong tendency to form positive ions in solution. The positive Zn^{2+} ions are attracted by the negatively charged Zn to reduce the metallic state of the metal. The potential of the Zn electrodes varies with the change in concentration of Zn^{2+} ions.

Figure 5.1.shows that the generation of Zn ions at 2 V was at the maximum (0.3 mg/ℓ). At 4 V and 6 V the rate of Zn^{2+} ions generation was at a minimum due to the occurrence of oxidation. This oxidation reaction inhibits the generation rate because of the Zn deposits on the SS electrode. The fluctuation of the 2 V Zn^{2+} ion generation is due to the increase and decrease of the uncontrolled current.

5.1.2 Constant flow rate SS–Zn electrochemical cell

Results obtained for the constant flow SS-Zn electrochemical cell are shown in Figure 5.2 (p. 23). A residence time of 10 min was maintained for water flowing through the cell. The current was set at 0.1 A and the potential difference was 2 V.

The following results were recorded for the constant flow SS–Zn electrochemical cell (Figure 5.2). The Zn ion generation increased constantly with time due to the constant current and potential difference in the electrochemical cell. The generation rate of the Zn ions also increased over time because of the continuous introduction of fresh feed into the system.

5.1.3 Two Zn electrode electrochemical cell (filtered water vs. rapid scaling solution)

Figure 5.3 (p. 23) shows that the generation of Zn^{2+} ions with RSS increased more than in the case of the filtered water. A metal with a high electropositive character will have a strong tendency to form positive ions in solution.

5.1.4 Constant flow rate Zn electrochemical cell (generation in raw brackish water)

Results obtained for a constant flow Zn electrochemical cell are shown in Figure 5.4 (p. 23). It shows that Zn^{2+} ions can be generated in raw brackish water. The parameters of the electrochemical cell were set at a potential difference of 2 V and a current of 0.1 A. The experiment was conducted using a dosing pump at different flow rates (pump speed). Figure 5.4 shows that at high flow rates the generation of Zn ions decreases. This is due to the decreased residence time of the Zn^{2+} ions in the generating cell.

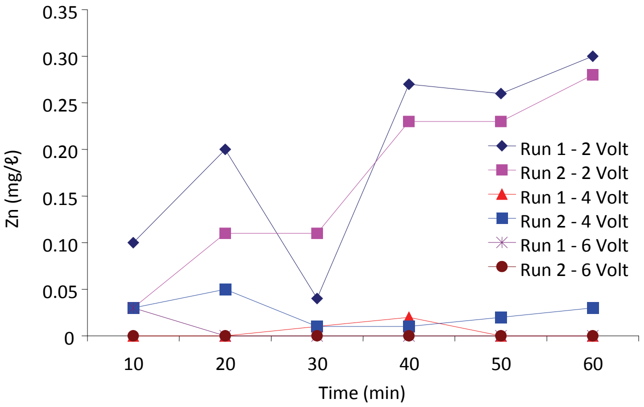

Figure 5.1: Results of SS–Zn electrochemical cell (filtered water)

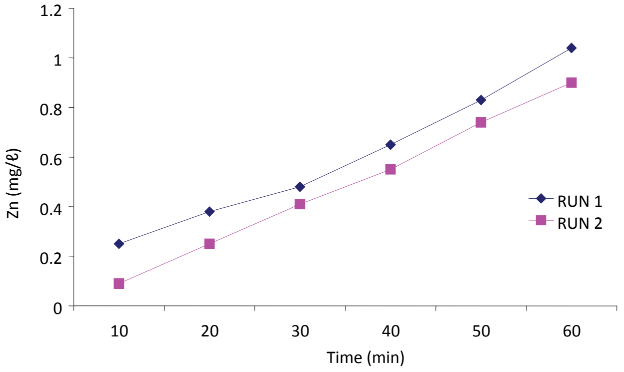

Figure 5.2: Results of constant flow SS-Zn electrochemical cell (filtered water)

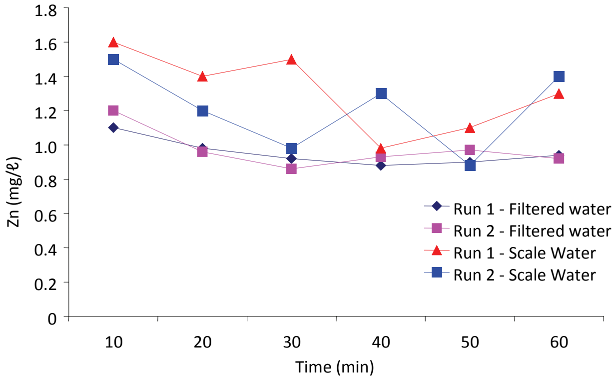

Figure 5.3: Results of two Zn electrode electrochemical cells
(filtered water vs. rapid scale solution)

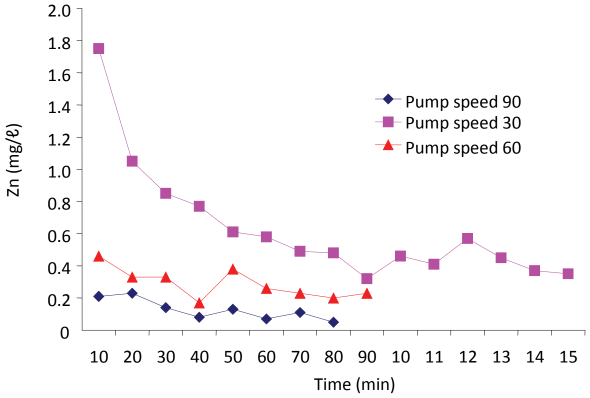

Figure 5.4: Results of constant flow Zn electrochemical cell (generation in raw brackish water) using three pump speeds (rpm)

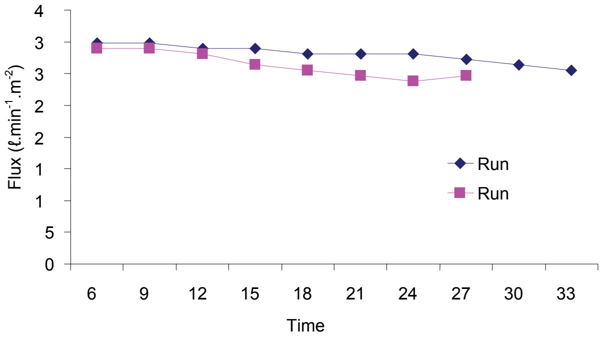

Figure 5.5: Reverse Osmosis run with rapid-scaling solution and no anti-scalant: flux

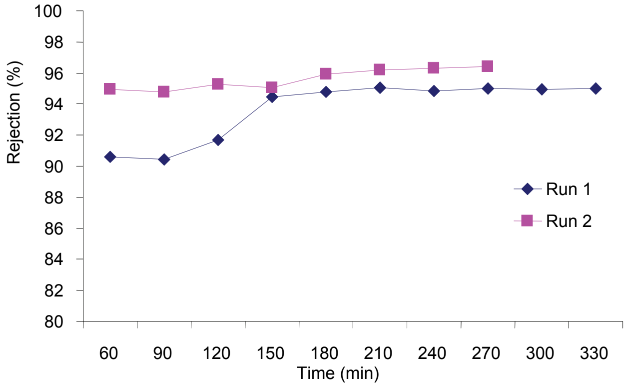

Figure 5.6: Reverse Osmosis run with rapid-scaling solution with no anti-scalant: rejection

5.2 Bench-scale RO Plant Results

Note that in all graphs the following units apply: rejection as % and flux as ℓ.min^{-1}.m^{-2}

5.2.1 Rapid-scaling solution with no anti-scalant added

The results for membrane flux and rejection were obtained for the RO runs in which no anti-scalants were included.

Figure 5.5 (p. 23) shows that the permeate flux decreased gradually with time due to the precipitation of salts on the membrane surface. Salts precipitation increased due to crystal growth. This precipitation forms a layer on the membrane surface that results in decreased permeates flux, and thus the loss of product quality.

Figure 5.6 (p. 23) shows that the rate of rejection increased with time. The system only stabilised after 3 h, where after the rejection rate increased to a constant value.

5.2.2 Rapid-scaling solution with commercial anti-scalant added

The results for membrane flux and rejection were obtained for the RO runs in which 2 mg/ℓ anti-scalant (Vitec 3000) were dosed continuously. In Run 1 the RO system ran for 3 h without the addition of anti-scalant, and the permeate flux decreased. In Run 2 anti-scalant was introduced after 3 h. Figure 5.7 shows that the permeate flux increased until it reached a constant value of 36.5 ℓ.min^{-1}.m^{-2}. Introduction of the anti-scalant prevented the crystal growth from occurring, and hence the flux was maintained. Figure 5.8 shows that the rejection increased slightly when the anti-scalant was introduced.

5.2.3 Rapid-scaling solution with Zn ions added (batch system)

This experiment ran for 3 h without an addition of an anti-scalant. Figure 5.9 shows that the flux decreased for that period. Zn^{2+} ions were generated for 10 minute periods in the feed tank, where after the zinc was fed into the system. The dosed Zn^{2+} ions delayed the crystal formation, and thus have a positive influence on the flux, as shown in Run 2. The flux remained constant for a short period of time, until 270 minutes, and thereafter decreased again. This change was ascribed to the low Zn^{2+} ion concentration in the system.

5.2.4 Rapid-scaling solution with Zn ions added (continuous dosing)

Figures 5.10 and 5.11 show the flux results of three RO runs during which different concentrations (75 µg/ℓ and 120 µg/ℓ effectively onto the membrane) of the Zn^{2+} ions were dosed. Zn^{2+} ions were dosed after 3 h of scaling. The introduction of Zn^{2+} ions inhibited the crystal growth and contributed to maintaining the permeate flux.

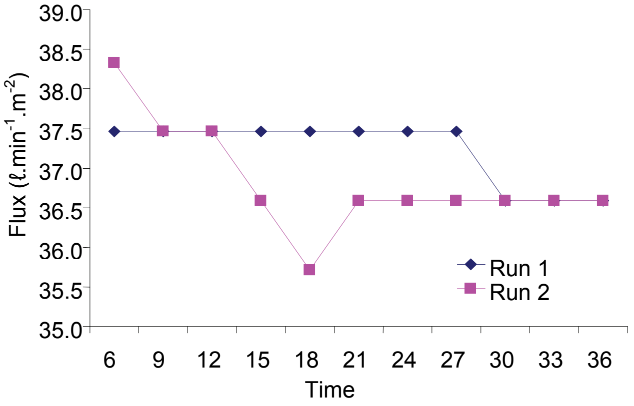

Figure 5.7: Reverse Osmosis run with rapid-scaling solution and commercial anti-scalant: flux

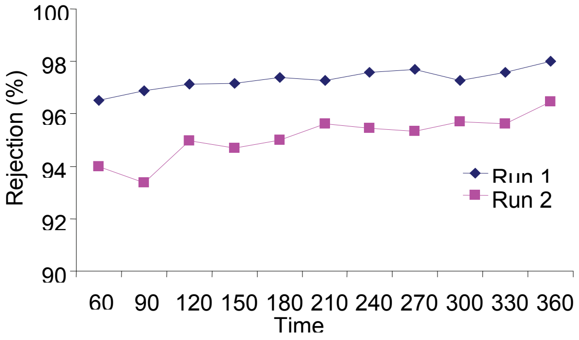

Figure 5.8: Reverse Osmosis run with rapid-scaling solution and Vitec anti-scalant: rejection

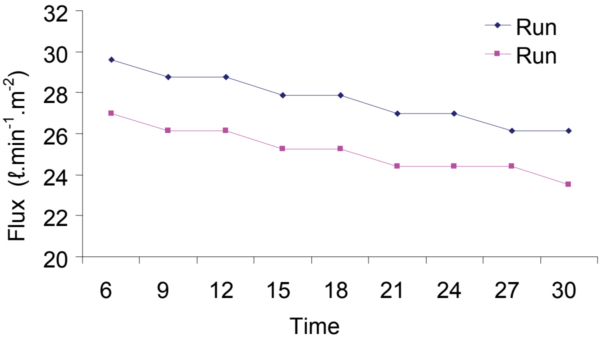

Figure 5.9: Reverse Osmosis run with rapid-scaling solution, with Zn^{2+} ions generated in a batch system: flux

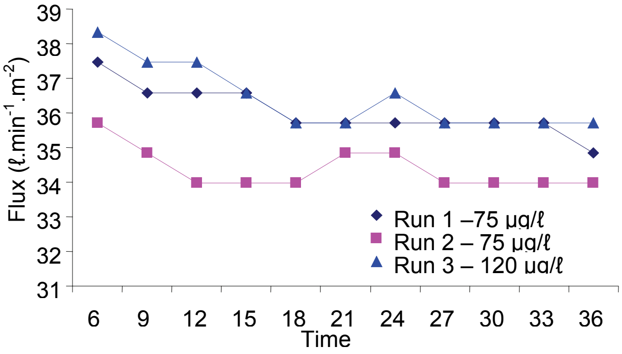

Figure 5.10: Reverse Osmosis run with rapid-scaling solution, with Zn^{2+} ions dosed in the feed line: flux

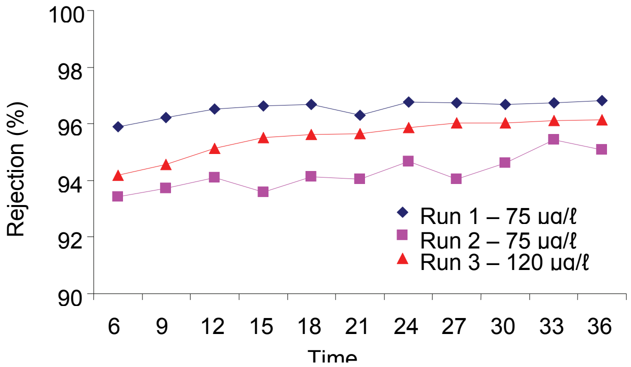

Figure 5.11: Reverse Osmosis run with rapid-scaling solution, with Zn^{2+} ions dosed in the feed line: rejection

5.3 Pilot Plant Results

The pilot plant was operational for more than 2 800 hours (well within specifications for such a system and membranes). Commercial Filmtec XLE-4040 membrane modules (98% rejection, as specified by the membrane manufacturer) were exposed to scaling groundwater: one module was used as the control, one was then exposed to commercial anti-scalant treatment with Vitec 3000, and the other to anti-scalant treatment with Zn^{2+} ions (accurate control over the Zn^{2+} concentration was problematic, but on average a Zn^{2+} concentration of less than 20 μg/ℓ in the feed water was generated).

The pilot plant had a constant flux of 40 ℓ.min^{-1}.m^{-2} for the first four weeks, as expected with the raw feed. Over the same period the rejection increased from approximately 92 to 97%, and stabilised slowly. After six weeks the flux started to decrease from 40 to 33 ℓ.min^{-1}.m^{-2}. The membrane flux of the commercial anti-scalant treated membranes stabilised at an average of 33 ℓ.min^{-1}.m^{-2} after 15 weeks. The membrane flux of the Zn^{2+} ions treated membranes decreased from 31 ℓ.min^{-1}.m^{-2} to 29 ℓ.min^{-1}.m^{-2} after 15 weeks. The membrane flux of the untreated feed decreased steeply to 27 ℓ.min^{-1}.m^{-2} over the same period, and continued to decline. The fluxes of the membranes treated with Zn^{2+} ions and commercial anti-scalant became similar, whereas the flux of the membrane without any anti-scalant decreased with time (see Figures 5.12 and 5.13).

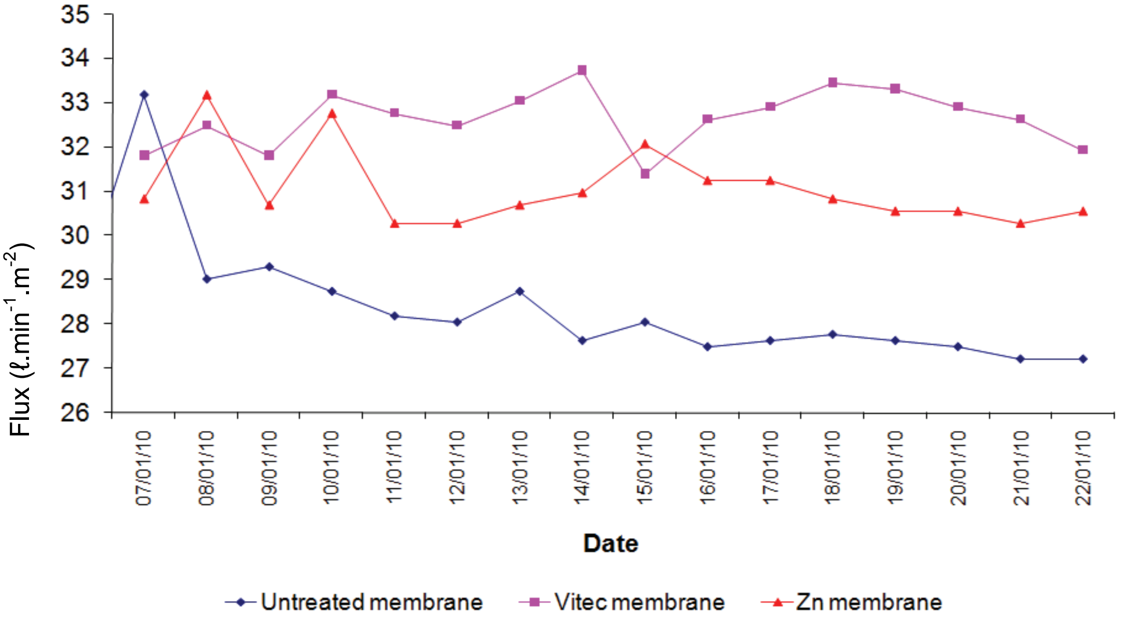

Figure 5.12: Pilot plant results: comparative results of membrane modules exposed to different anti-scaling treatments: flux vs. time over the last 15 days of monitoring

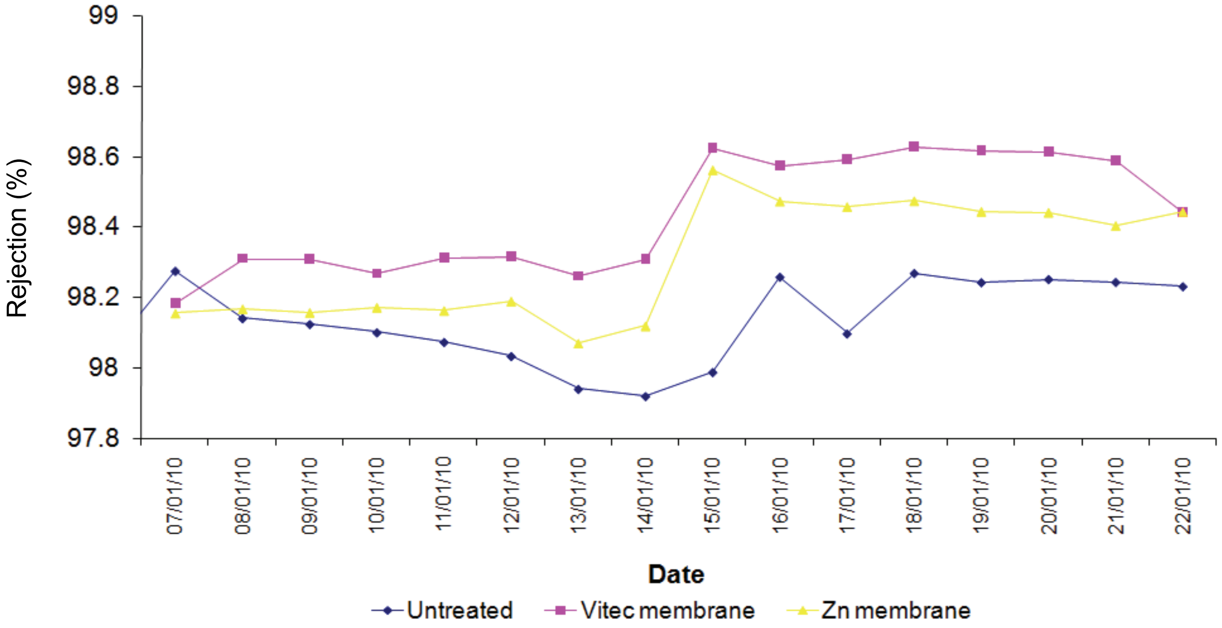

Figure 5.13: Pilot plant results: comparative results of membrane modules exposed to different anti-scaling treatments: rejection vs. time over the last 15 days of monitoring

6 RESULTS AND DISCUSSION: APPLICATION OF A MAGNETIC FIELD

6.1 Flat-cell Membrane Experiments

Unfortunately the results, both with and without the AC magnetic field, were not reproducible. They were sensitive to the rate and method of adding the RFS. When three very similar results were obtained both with and without the AC magnetic field, it had to be concluded that the AC field had no effect on RFS fouling. Hence, a 50 Hz AC magnetic field (RMS amplitude approximately 80 Gauss) has no descaling effect on a flat-cell membrane under the conditions described in this report. A typical result is shown in Figure 6.1. As the consultancy called for more realistic field trials involving a spiral-wrap membrane, these were also carried out (Section 6.2).

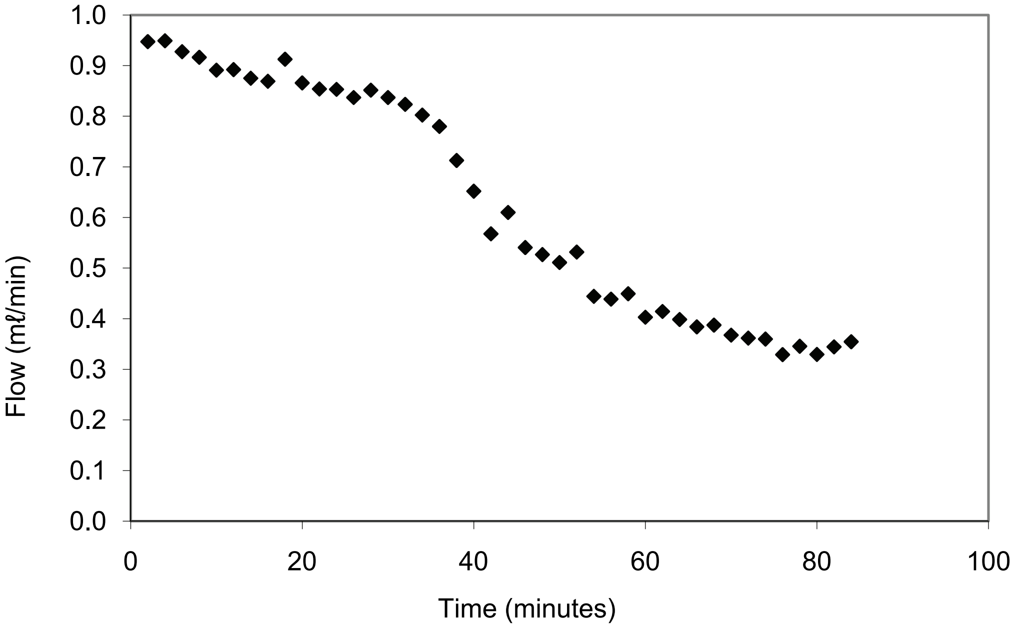

Figure 6.1: Typical RO flux results for flat-cell experiments (RFS and a 50 Hz magnetic field – perpendicular)

6.2 Spiral-wrap Membrane Experiments

These experiments were carried out over a period of 20 days. Results are presented in Table 6.1 and plotted in Figure 6.2. (For the sake of clarity, only the points at the beginning of each day are plotted). As can be seen, over a period of 19 days there was no improvement in the fouling rate of a spiral element placed in an AC magnetic field compared with a similar element with no field.

The experiments were carried out in the RO plant at Ikusasa, with an AC magnetic field applied perpendicular to the membrane.

Table 6.1: Results of spiral-wrap membrane experiments (over 20 days)

Time Days	Brine (ℓ/h)	P1 (ℓ/h)	P2 (ℓ/h)	Conductivity P1 (µs.cm^{-1})	Conductivity P2 (µs.cm^{-1})	P1 (°C)	P2 (°C)	Feed pressure (kPa)	Conductivity Feed (µs.cm^{-1})	Feed (°C)
0.00	280	150	150	11.0	11.3	26.5	26.7	240	131.0	24.2
1.00	270	160	165	10.6	10.8	26.3	26.3	250	126.2	25.2
2.00	250	165	165	11.1	11.6	26.7	26.7	250	129.7	25.5
3.00	255	165	170	11.0	11.6	26.5	26.5	250	131.5	23.9
4.00	250	155	155	11.1	10.9	26.7	26.6	250	135.9	24.9
5.00	250	135	145	11.8	12.8	16.9	27.0	220	136.0	27.0
6.00	240	150	150	12.0	11.1	26.5	26.5	250	138.5	27.4
7.00	225	145	150	15.3	12.9	27.3	27.2	250	140.0	25.1
8.00	215	130	130	15.4	13.6	26.7	26.9	250	140.0	24.8
9.00	225	115	115	15.1	13.5	26.4	27.4	250	140.2	24.6
10.00	260	110	115	16.3	14.0	26.7	27.1	250	134.5	26.8
11.00	255	115	115	17.3	13.8	26.9	27.0	250	127.0	26.9
12.00	220	105	110	17.9	14.6	27.0	27.1	250	123.0	25.3
13.00	255	110	115	15.2	14.6	27.0	27.1	250	125.5	25.7
14.00	255	105	110	16.7	15.8	26.7	27.1	250	133.9	26.3
15.00	250	115	120	16.5	14.3	26.2	26.6	250	120.5	23.2
16.00	245	110	115	16.8	15.1	26.3	26.6	250	111.5	23.0
17.00	265	105	110	16.4	15.4	25.6	26.1	250	114.4	22.6
18.00	265	105	110	19.7	17.4	26.1	26.2	250	113.0	25.1
19.00	250	110	115	16.9	15.6	26.5	26.5	250	114.1	25.6

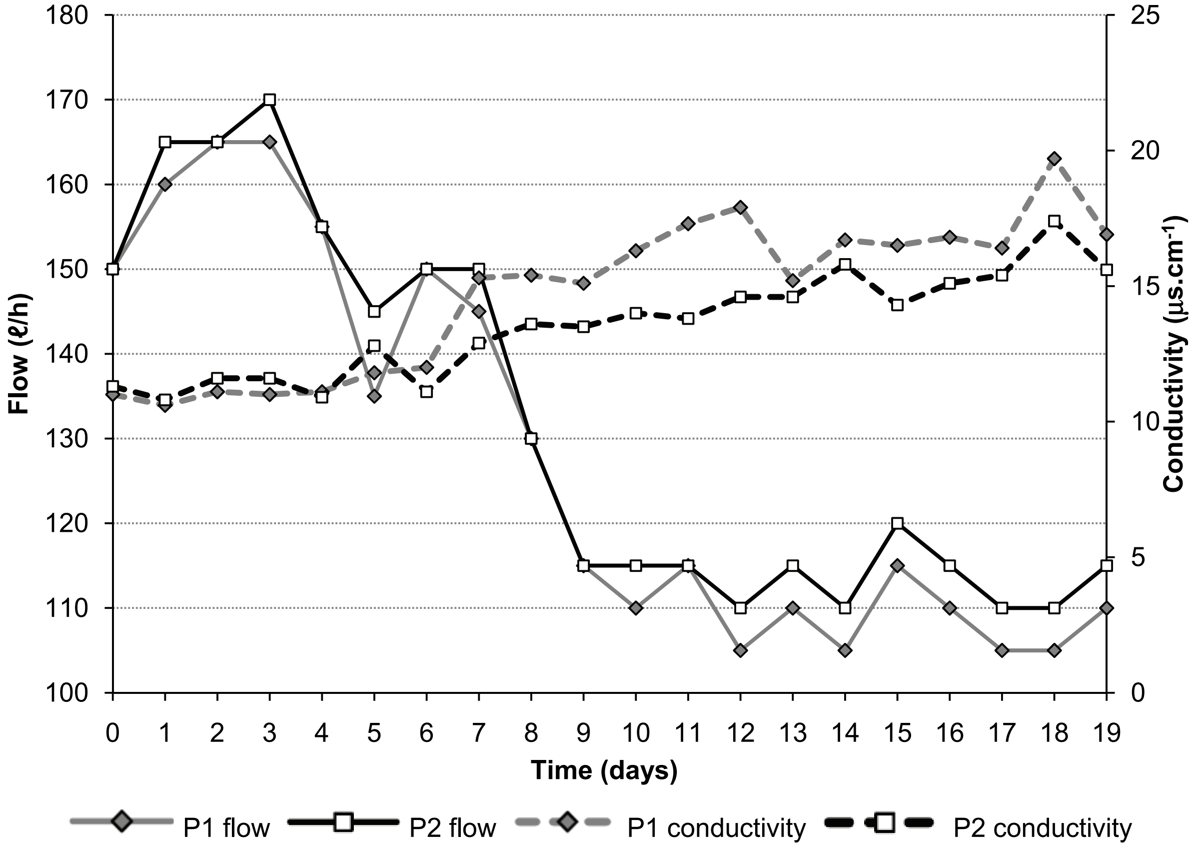

Figure 6.2: Membrane performance as a result of magnetic anti-scale treatment on spiral-wrap membranes (over 19 days)

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

7.1.1 Introduction of Zn^{2+} ions

Fresh ionic Zn^{2+} ions have been successfully generated and verified on laboratory and pilot plant scale. Different configurations for Zn^{2+} ion generation were evaluated. A flat test cell was calibrated and used for the laboratory investigation, while a 600 ℓ/h pilot plant was used for longer trail runs. In all three instances commercially available anti-scalants were used as reference, while untreated membranes were also used as comparison, in addition to the fresh addition of Zn^{2+} ions.

A literature study was compiled on the current status of freshly generated Zn^{2+} ions for the prevention of specifically $CaCO_3$ scaling on RO membranes.

No direct comparison could be made between the successful generations of fresh Zn^{2+} ions for the prevention of scaling, with that of the application of a magnetic field (the latter was unsuccessful).

Based on the findings of Zn generation and application, the following points were concluded:

- The Zn^{2+} concentration is at a maximum at a potential difference of 2, compared to 4 and 6 V, using a Zn and SS electrode in solution.
- The generation of Zn^{2+} ions increased constantly with time due to the constant current and potential difference in the electrochemical cell.
- The amount of Zn^{2+} ions generated with a laboratory prepared RSS increased more than with the filtered water due to the pH difference.
- Zinc ions can be generated in both raw brackish water and laboratory prepared scaling solutions.
- Although the use of a commercial anti-scalant still yielded the best membrane performance results in the pilot plant study, it has been shown that Zn^{2+} ions in low concentrations (<120 µg/ℓ) can potentially be optimised as an alternative, or supplement, to other $CaCO_3$ anti-scalants, depending on the feed water quality.
- As the running cost of Zn^{2+} generation is practically only made up by electricity usage (which is only a fraction of the cost of running the RO plant), the potential cost saving can roughly equal the current cost of anti-scalant (e.g. in the case of Bitterfontein, this saving can be up to R0.40/kℓ).

7.1.2 Application of a magnetic field

Flat-cell

No improvement in the fouling rate was observed for the experiments using a RFS in a flat-cell with an AC magnetic field applied perpendicular to the membrane. Nor was any improvement observed in the fouling rate of a spiral element place in an AC magnetic field compared with a similar element with no field, over a period of 14 days.

A 50 Hz AC magnetic field (RMS amplitude approximately 80 Gauss) has no de-scaling effect on a flat-cell membrane under the conditions described in this report.

Spiral-wrap element
An AC magnetic field with the orientation and magnitudes used here has no effect on the scaling of the RO membrane used in these experiments.

7.2 Recommendations

7.2.1 Introduction of Zn^{2+} ions

- Due to Zn metal attack, it is recommended that ions should be generated at low voltages if high salt concentrations are going to be encountered.
- Feed water should be analysed before deciding which anti-scalant is to be added to the water, as Zn^{2+} will only be effective against $CaCO_3$ scaling.
- The oxidation potential reaction in Zn^{2+} ions at different potential differences should be investigated, due to the sensitivity of thin film composite membranes to oxidation.
- More online Zn^{2+} ion generation investigation should be conducted to optimise the Zn^{2+} ion generation as an alternative to chemical anti-scalants for $CaCO_3$ scaling waters.
- Membrane autopsy should be carried out in follow-up research using SEM, to determine the crystal morphology on the membrane.
- A software package such as FT Norm® should be used to normalise plant performance data in terms of temperature and pressure.

7.2.2 Application of a magnetic field

It is recommended that no further RFS flat-cell experiments be carried out due to the difficulty of obtaining reproducible results and the apparent lack of an effect.

If the work on spiral wrap elements is to be continued, it will be necessary that the existing membrane elements be cleaned (or better still replaced) and the experiment be run again at higher RMS magnetic fields. In the event of replacement the present elements should be taken apart and the membrane surfaces be examined, using a SEM, for changes in the morphology in regions where the field was high, low and essentially zero (at the end of the element). In the event of non-replacement both elements should be cleaned and the experiment rerun before both elements are examined for morphology changes as above.

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APPENDIX A: CALCULATIONS

A.1 Flux calculation equation

$$Flux = \frac{flowrate}{Area}$$

where the flow rate is the permeate flow rate taken over 5 min. This value is then converted to ℓ/hr.

The area in the equation is the active area of the membrane.

See the example below.

Data from Table B6 (Appendix B), Results of RO Run 1 with RSS with no anti-scalant:

Permeate flow rate at 60 min:	40 mℓ/5min ≈ 48 ℓ/hr
Active membrane area:	0.013775 m^2

$$Flux = \frac{flowrate}{Area}$$

$$Flux = \frac{48}{0.013775}$$

$Flux = 34.85\ \ell.hr^{-1}.m^{2}$

This value was then used in the figure showing the flux of the RO run with RSS with no anti-scalant, at the 60 min interval (Figure 5.5).

A.2 Rejection calculation equation

$$\%Rejection = \frac{(EC.Feed - EC.Perm)}{EC.Feed} \times 100$$

where EC feed is the electrical conductivity of the feed and the EC perm the electrical conductivity of the permeate.

Data of the following example was collected from Table B6 (Appendix B), Results of RO Run 1 with RSS solution with no anti-scale or supplements.

Feed electrical conductivity at 60 min:	1189 µS/cm
Permeate electrical conductivity at 60 min:	112 µS/cm

$$\%\mathrm{R}ejection = \frac{(EC.Feed - EC.Perm)}{EC.Feed} \times 100$$

$$\%\ Rejection = \frac{(1189 - 112)}{1189} \times 100$$

$$\%\ Rejection = 90.58\%$$

This value was then used in the figure showing the flux of the RO run with RSS with no anti-scalant, at the 60 min interval (Figure 5.5).

APPENDIX B: RAW DATA – ZN GENERATION

Table B1: Results of SS–Zn electrochemical cell at 2 V setting (filtered water)

Time (min)	Run 1		Run 2	
	Amps	Zn (mg/ℓ)	Amps	Zn (mg/ℓ)
10		0.1	0.114	0.03
20	0.152	0.2	0.14	0.11
30	0.157	0.04	0.138	0.11
40	0.14	0.27	0.111	0.23
50	0.131	0.26	0.108	0.23
60	0.103	0.3	0.101	0.28

Table B2: Results of SS–Zn electrochemical cell at 4 Volt setting (filtered water)

Time (min)	Run 1		Run 2	
	Amps	Zn (mg/ℓ)	Amps	Zn (mg/ℓ)
10	0.983	0	1.023	0.03
20	1.031	0	0.917	0.05
30	0.962	0.01	0.891	0.01
40	0.948	0.02	0.858	0.01
50	0.884	0	0.829	0.02
60	0.9	0	0.767	0.03

Table B3: Results of SS–Zn electrochemical cell at 6 Volt setting (filtered water)

Time (min)	Run 1		Run 2	
	Amps	Zn mg/ℓ	Amps	Zn mg/ℓ
10	2.45	0.03	2.18	0
20	2.07	0	2.1	0
30	1.93	0	2.02	0
40	1.87	0	2.12	0
50	1.78	0	1.95	0
60	1.73	0	1.76	0

Table B4: Results of constant flow SS–Zn electrochemical cell (filtered water)

RUN 1				RUN 2			
Time (min)	mg/ℓ	mg	Generation rate	Time (min)	mg/ℓ	mg	Generation rate
10	0.25	250	0.25	10	0.09	90	0.09
20	0.38	380	0.13	20	0.25	250	0.16
30	0.48	480	0.10	30	0.41	410	0.16
40	0.65	650	0.17	40	0.55	550	0.14
50	0.83	830	0.18	50	0.74	740	0.19
60	1.04	1040	0.21	60	0.9	900	0.16

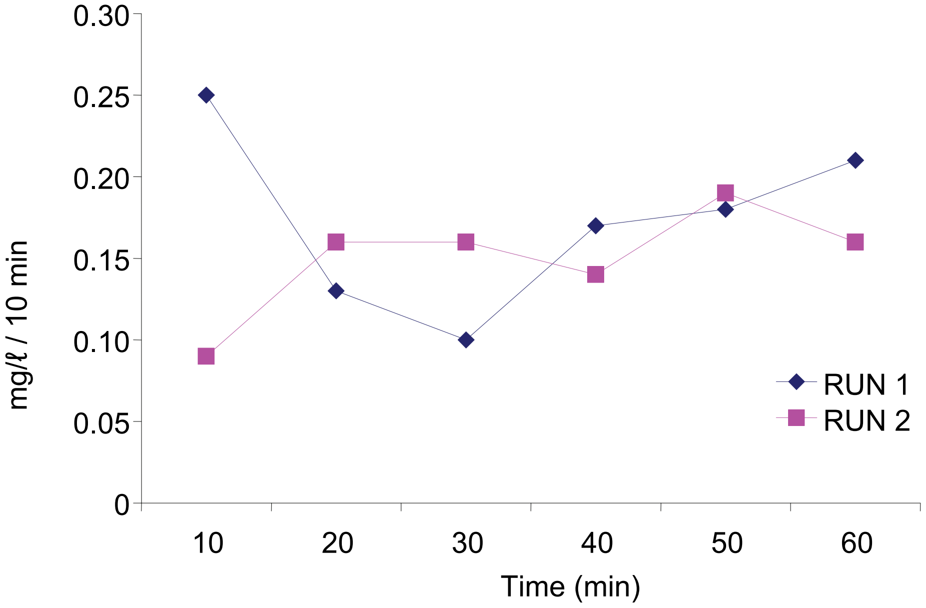

Figure B1. Generation rate of constant flow SS–Zn electrochemical cell (filtered water).

Table B5: Constant flow Zn electrochemical cell with variable pump speed (generation in RSS)

Time (min)	Pump speed 30		Pump speed 60		Pump speed 90	
	mg/ℓ	µg	mg/ℓ	µg	mg/ℓ	µg
10	1.75	1750	0.46	460	0.21	210
20	1.05	1050	0.33	330	0.23	230
30	0.85	850	0.33	330	0.14	140
40	0.77	770	0.17	170	0.08	80
50	0.61	610	0.38	380	0.13	130
60	0.58	580	0.26	260	0.07	70
70	0.49	490	0.23	230	0.11	110
80	0.48	480	0.2	200	0.05	50
90	0.32	320	0.23	230		
100	0.46	460				
110	0.41	410				
120	0.57	570				
130	0.45	450				
140	0.37	370				
150	0.35	350				

Table B6: Results of RO run 1 with RSS, with no anti-scalant

Time (min)	Flow rate permeate	Flow rate permeate (ℓ/h)	Flux	Pump RPM (Hz)	EC feed	EC permeate	Rejection
60	40	0.48	34.85	26.3	1189	112	90.58
90	40	0.48	34.85	26.1	1069	102	90.46
120	39	0.47	33.97	25.6	1182	98	91.71
150	39	0.47	33.97	26.2	1171	65	94.45
180	38	0.46	33.10	25.9	1262	66	94.77
210	38	0.46	33.10	25.1	1248	62	95.03
240	38	0.46	33.10	25.3	1205	62	94.85
270	37	0.44	32.23	25.1	1158	58	94.99
300	36	0.43	31.36	23	1147	58	94.94
330	35	0.42	30.49	24.5	1122	56	95.01

Table B7: Results of RO run 2 with RSS, with no anti-scalant

Time (min)	Flow rate permeate	Flow rate permeate (ℓ/h)	Flux	RPM (Hz)	EC feed	EC permeate	Rejection (%)
60	39	0.47	33.43	26.3	1162	58.9	94.93
90	39	0.47	33.43	26.1	890	46.2	94.81
120	38	0.46	32.57	25.1	1220	57.6	95.28
150	36	0.43	30.86	26.8	1092	54	95.05
180	35	0.42	30.00	25.6	1135	46	95.95
210	34	0.41	29.14	25.6	1075	40.9	96.20
240	33	0.40	28.29	24.7	1212	44.6	96.32
270	34	0.41	29.14	22.3	1184	42.3	96.43

Table B8: Results of RO run 1 with RSS and Vitec

Time (min)	Flow rate permeate	Flow rate permeate (ℓ/h)	Flux	Pump RPM (Hz)	EC Feed	EC permeate	Rejection
60	43	0.516	37.46	26.9	1258	43.90	96.51
90	43	0.516	37.46	25.8	1211	37.8	96.88
120	43	0.516	37.46	26.1	1296	37.2	97.13
150	43	0.516	37.46	26.9	1305	37.2	97.15
180	43	0.516	37.46	26.3	1142	29.8	97.39
210	43	0.516	37.46	26.7	1075	29.2	97.28
240	43	0.516	37.46	25.6	1116	26.9	97.59
270	43	0.516	37.46	25.4	929	21.3	97.71
300	42	0.504	36.59	25.1	1023	27.8	97.28
330	42	0.504	36.59	26.5	878	21.3	97.57
360	42	0.504	36.59	24.9	1066	21.3	98.00

Table B9: Results of RO run 2 with RSS and Vitec

Time (min)	Flow rate permeate	Flow rate permeate (ℓ/h)	Flux	Pump RPM (Hz)	EC feed	EC permeate	Rejection (%)
60	44	0.53	38.33	25.9	1369	82.2	94.00
90	43	0.52	37.46	24.2	1275	84.5	93.37
120	43	0.52	37.46	25.3	1018	51.3	94.96
150	42	0.50	36.59	25	1110	58.9	94.69
180	41	0.49	35.72	25.6	1066	53.2	95.01
210	42	0.50	36.59	25.8	945	41.4	95.62
240	42	0.50	36.59	24.9	1096	49.8	95.46
270	42	0.50	36.59	24.8	1068	49.8	95.34
300	42	0.50	36.59	25.3	1103	47.4	95.70
330	42	0.50	36.59	26.5	960	42.1	95.61
360	42	0.50	36.59	25.6	1203	42.6	96.46

Table B10: Results of RO run 1 with RSS, with Zn ions dosed in the feed line

Time (min)	Flow rate permeate	Flow rate permeate (ℓ/h)	Flux	Pump RPM (Hz)	EC feed	EC permeate	Rejection (%)	Time (min)
60	43	0.52	37.46	25.1	0	1239	50.8	95.90
90	42	0.50	36.59	25.4	0	1198	45.3	96.22
120	42	0.50	36.59	25.6	0	998	34.8	96.51
150	42	0.50	36.59	25.6	0	1098	37.1	96.62
180	41	0.49	35.72	25.2	0	1002	33.1	96.70
210	41	0.49	35.72	24.7	100	1363	50.3	96.31
240	41	0.49	35.72	24.9	60	1274	41.3	96.76
270	41	0.49	35.72	25.3	30	1273	41.5	96.74
300	41	0.49	35.72	25.4	60	1248	41.4	96.68
330	41	0.49	35.72	24.8	60	1236	40.3	96.74
360	40	0.48	34.85	24.7	140	1245	39.7	96.81

Table B11: Results of RO run 2 with RSS, with Zn ions dosed in the feed line

Time (min)	Flow rate permeate	Flow rate permeate (ℓ/h)	Flux	Pump RPM (Hz)	Zn conc. in feed line (mg/ℓ)	EC feed	EC permeate	Rejection (%)
60	41	0.49	35.72	26.1	0	1278	84.0	93.43
90	40	0.48	34.85	25.8	0	1261	79.1	93.73
120	39	0.47	33.97	24.9	0	1221	71.9	94.11
150	39	0.47	33.97	25.1	0	1217	78.0	93.59
180	39	0.47	33.97	25.0	0	789	46.3	94.13
210	40	0.48	34.85	25.1	30	1160	69.1	94.04
240	40	0.48	34.85	25.9	110	1118	59.5	94.68
270	39	0.47	33.97	25.4	60	1117	66.5	94.05
300	39	0.47	33.97	24.9	40	1307	70.3	94.62
330	39	0.47	33.97	25.6	30	1327	60.7	95.43
360	39	0.47	33.97	25.9	100	1356	66.7	95.08

Table B12: Results of RO run 2 with RSS, with Zn ions dosed in the feed line

Time (min)	Flow rate perm.	Flow rate perm. (ℓ/hr)	Flux	Pump RPM (Hz)	Zn conc. (mg/ℓ)	EC feed	EC perm.	Rejection
60	44	0.53	38.33	25.6	0	1238	72.1	94.18
90	43	0.52	37.46	25.2	0	1224	66.4	94.58
120	43	0.52	37.46	25.6	0	1248	60.6	95.14
150	42	0.50	36.59	24.9	0	1379	61.9	95.51
180	41	0.49	35.72	26.4	0	1151	50.5	95.61
210	41	0.49	35.72	25.6	100	1369	59.7	95.64
240	42	0.50	36.59	25.6	110	1168	48.1	95.88
270	41	0.49	35.72	26.4	150	1260	49.9	96.04
300	41	0.49	35.72	25.6	130	1120	44.3	96.04
330	41	0.49	35.72	25.3	210	1066	41.3	96.13
360	41	0.49	35.72	25.1	150	1270	49	96.14

Table B13: Filtered water generation vs. scale water generation

Time (min)	Filtered water		Scale water	
	Run 1	Run 2	Run 1	Run 2
10	1.1	1.2	1.6	1.5
20	0.98	0.96	1.4	1.2
30	0.92	0.86	1.5	0.98
40	0.88	0.93	0.98	1.3
50	0.9	0.97	1.1	0.88
60	0.94	0.92	1.3	1.4