Pre-Treatment Procedures to Control Biogrowth and Scale Formation in Membrane Systems

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ABSTRACT

The Middle East region is regarded as the cradle of desalting, having many of the world's largest membrane systems in addition to extensive thermal distillation plants. Many important design and operation techniques have been developed and perfected in the region because of the need to solve problems locally.

Efficient pre-treatment design and operation is essential for the optimisation of RO plant performance irrespective of whether the feed source is natural or waste water. Poorly designed pre-treatment and inadequate plant maintenance has often resulted in membrane failure and tarnished the reputation of the reverse osmosis process.

This paper examines the importance of monitoring pre-treatment plants used to control microbiological and general fouling and inhibiting the formation of inorganic scales. It also gives examples of systems that have experienced problems and the technical recommendations made to improve pre-treatment so as to improve membrane performance and operating costs.

INTRODUCTION

Pre-treatment systems for RO plants are designed to produce a feedwater with a reduced fouling potential by removing particulates, micropollutants and micro-organisms as well as preventing the formation of inorganic scales.

The basic design of RO plants in the Middle East is similar to those used elsewhere (Figure 1). The only significant difference is the use of sea water with high salinity and temperature, and the hot ground waters found in Saudi Arabia that require the use of cooling systems, which can bring their own problems.

The warm climate of this region makes biofouling the greatest potential problem, so specific pre-treatment requirements are essential. However, many of these fouling situations can be reduced or eliminated by improved system design and better plant maintenance procedures.

THE IMPORTANCE OF FEEDWATER QUALITY

Eliminating or reducing micropollutants in the feedwater minimises membrane fouling, thus maintaining a good production rate, a low salt passage and an extended membrane lifetime.

The complexity of the pre-treatment system varies greatly depending on the source and analysis of the feed stream and the size of the membrane system involved. This can vary from a simple micron cartridge filter to a sophisticated system that may include ozonation, DAF, lime/soda softening, clarification, media filtration and cartridge filters.

Although cost considerations may dictate the final choice of system, cost alone should not be the overriding factor. It is essential to understand that a plant designed with a good pre-treatment system will have less downtime, require less cleaning, be easier and cheaper to maintain and have a significantly longer lifetime.

Capital cost and operating economics are important issues in considering what type of pre-treatment to use. This is invariably linked to plant output with water softeners used to reduce feedwater hardness in small industrial systems. It makes little sense to build an extensive and expensive pre-treatment plant in front of a tiny membrane system, even if needed. In this case, it is more economical to just use a cartridge filter and replace the membranes more frequently.

In addition to the capital equipment, there are a range of on-going chemical treatments that may be used. These include: sodium hypochlorite and other biocides, ferric chloride and polymeric flocculants, mineral acids and antiscalants, and sodium bisulphite.

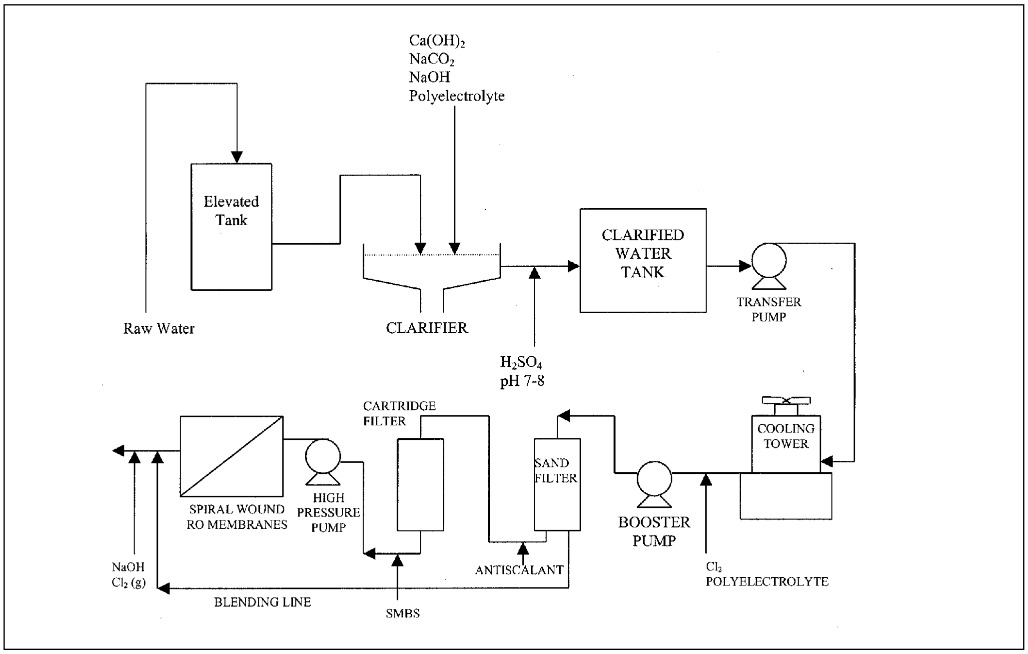

Figure 1 — ***Example of RO pre-treatment plant***

Feedwater quality dictates the performance of the membrane system, which in turn limits system recovery, plant output rate and water quality. It is essential to monitor feedwater quality and the performance of the individual pre-treatment system components so as to optimise plant economics and efficiency. Feedwater quality is normally characterised by the silt density index (SDI).

The calcium carbonate scaling potential is determined by the Langelier Saturation Index (LSI), or the Stiff & Davis Saturation Index (S&DSI) for high ionic strength waters. Other scalants such as calcium sulphate and silica are determined by measuring their ionic concentration against their known solubility products.

The plant operator must measure SDI and scaling potential in order to monitor and control membrane fouling. The membrane manufacturers recommend operation at SDI levels <3 for hollow fibre and <5 for spiral wound elements. The SDI is a guide to the colloidal fouling potential. A 'clean' brackish water will typically have an SDI <3, whereas sea water will have significantly higher SDI with values of 6–20. With sea water, it is common practice to use beach wells rather than surface intakes to provide a 'cleaner' water source. With surface waters (rarely found in the Middle East Region), SDI levels above 150 are common.

The total dissolved solids (TDS) is also measured. For brackish water, the TDS will be less than 15,000 ppm and for sea water 40,000–55,000 ppm. The TDS dictates the natural osmotic pressure and hence the system operating pressure. The TDS (or ionic strength) also affects the scaling potential of all the scaling species present.

It is necessary to make a full and detailed water analysis to identify all major anions and cations that contribute to scale formation and general fouling. The major scaling/fouling ions are calcium, magnesium, bicarbonate, sulphate, silica, iron and barium. The fluoride and strontium levels should also be measured, although these are rarely a problem.

When calculating the saturation index of calcium carbonate using the LSI for brackish water and S&DSI for sea water, the alkalinity and calcium ion concentration with TDS and temperature is needed.

Chemical treatment using acid and/or antiscalants is needed to inhibit scaling. The use of a good antiscalant will enable plant operation at higher LSI or S&DI values. An effective antiscalant permits plant recovery to be increased to an LSI of +2.6 compared to LSI +1.0 when using a commodity antiscalant such as sodium hexametaphosphate.

Microbiological analyses are needed to monitor biological activity and biofouling potential throughout the pre-treatment and membrane systems. Most surface waters and sea waters also require determination of humic acid content. These are complex organic molecules that have been shown to cause severe membrane fouling and can greatly contribute to biofouling situations.

The presence of soluble ferrous iron as Fe^{2+} or insoluble ferric ions as Fe^{3+} should also be measured as they often cause a fouling problem if not adequately removed by the pre-treatment plant. Although ferrous ions are soluble, there is a risk of oxidation to insoluble ferric salts. For this reason, ferrous ions are often deliberately oxidised by chlorine and removed by filtration. Some natural water sources have a high iron content (up to 20 ppm), but it is also common for the pre-treatment plant itself to be the source of iron contamination either due to corroded pipework, particularly with low pH acid dosed systems, or the overdosing of ferric chloride when used as a coagulant.

The measurement of pH should always be carried out at the time of sampling, as pH will vary with temperature and the carbon dioxide equilibrium.

PRE-TREATMENT OPTIONS

There are several options for mechanical and chemical pre-treatment to control fouling and microbiological growth.

Minimum pre-treatment is required for a 'clean' well water with a low SDI <2 and a temperature acceptable to the membrane. In this case, a 10 micron cartridge filter and antiscalant dosing to prevent scale formation will usually suffice.

For larger systems, additional flocculation and filtering procedures may be required to remove suspended solids. It is common to chlorinate the feedwater to control microbiological growth, and it is often necessary to dechlorinate with sodium bisulphite prior to the water entering the membranes.

Ground water normally has a higher TDS than surface water but is usually low in suspended solids and organic content. The limiting factor for membrane fouling in ground water is the quantity of calcium, alkalinity and iron present.

The composition of surface water from the sea, rivers or lakes may vary with seasonal changes where the fouling potential is mainly dictated by the composition of silts, suspended solids and naturally occurring organic compounds such as humic substances. Other important composition changes are due to algal blooms, salinity and temperature, both seasonal and due to storms. Also, the sea is tidal, twice a day, which may have a significant impact in plants using surface sea water.

For medium-sized plants (1,000 to 5,000m^3/day), the most frequently selected methods of mechanical pre-treatment are the use of sand and multi-media filters, granular activated carbon (GAC) and cartridge filters. However, ultrafiltration membranes have also been considered as a suitable pre-treatment for some municipal RO installations. Although this technology is still in its infancy and is seldom economically viable, it presents a good prospect for the future.

Figure 2 — ***Sand filters for brackish water pre-treatment***

Multi-media filters and sand filters (Figure 2) are designed to remove suspended solids typically >30 micron, reducing the SDI to <4. These particles occur naturally in the raw water and are agglomerated and flocculated by chemicals such as ferric chloride, alum and polymers.

GAC is used to remove residual chlorine and to adsorb organics, but a small rise in SDI may be observed. However, a 5 or 10 micron cartridge filter should always be used as the final protection before the membrane, reducing the SDI to <3. The cartridge filters will also protect the membranes if the pre-treatment plant fails. Multi-media and carbon filters are usually the most costly parts of these pre-treatment systems.

For many of the large inland plants, it is essential to operate at as high a recovery as possible so as to optimise the volume of feedwater and minimise the brine discharge. At recoveries of 80–90%, with some of the hard brackish waters found in the region, the membranes would irreversibly foul or scale in a very short time. The problem is often made worse by the excessive temperature of deep well water sources that entail the use of cooling towers, which in these severe operating conditions soon choke with algae, sand and scale.

To overcome these problems, plant users such as Riyadh Water Authority use more complex and expensive pre-treatment systems including lime/soda softening and clarification, cooling system, filtration systems, and the extensive use of flocculants, pH control and antiscalants. These types of pre-treatment plants effectively reduce the calcium, alkalinity, iron and silica levels of the raw water, thus allowing operation at significantly higher conversion rates.

In the majority of medium and large systems, chlorination is used to control biological fouling, followed by dechlorination with sodium bisulphite. It should be noted that even where sodium bisulphite is used, there have been many recorded cases of membrane damage due to chlorine attack. To help prevent chlorination damage, it is essential that an effective redox alarm system be used. Care must also be taken to ensure that chlorine does not enter the membrane from other sources such as flushing water or 'drawback' of chlorinated potable supply.

Where cellulose acetate membranes are used, pH control is required to prevent membrane hydrolysis.

MONITORING PRE-TREATMENT PERFORMANCE

An important aspect for trouble-free operation is the regular monitoring of feedwater condition throughout the pre-treatment system and regular inspection of equipment and pipework. Analysing samples of feedwater at each treatment stage enables a good assessment to be made of plant performance.

A careful inspection of pipework, dosing tanks and cartridge filters can identify biofilm formation at an early stage, prompting sanitisation procedures and in some cases preventing widespread biofouling. Where an ineffective antiscalant programme is not being used or the pre-treatment has failed, visual inspection may show colloidal particles, iron or inorganic scale on the cartridge filter fabric.

Monitoring procedures should be routine with readings plotted either electronically or by hand (Figure 3). Graphs should be prepared, dated and filed appropriately with any unusual or erratic results highlighted with explanations and comments.

There are a number of monitoring systems available to record the important parameters such as pressure drop, output, pH, conductivity and TOC. Many of these systems incorporate an alarm to alert the operator when parameters exceed fixed limits.

In addition to standard instrumentation, operators must understand the importance of visual examination of the pre-treatment system. They must be trained to interpret the data correctly so that operating problems can be detected early before fouling or membrane damage becomes irreversible.

The majority of fouling situations that we have seen were due to poor plant monitoring and an inadequate awareness by plant operators of the significance of 'apparent' small changes in feedwater composition or operating parameters.

CONSEQUENCES OF POOR PRE-TREATMENT

There are many reasons why the pre-treatment system may fail during the lifetime of the plant (Figures 4 and 5). It should be assumed that failures will happen and design features and monitoring procedures should detect these occurrences early so as to minimise their effects. Table 1 summarises some of the most commonly seen failures and suggests monitoring practices to recognise the problems at the earliest opportunity.

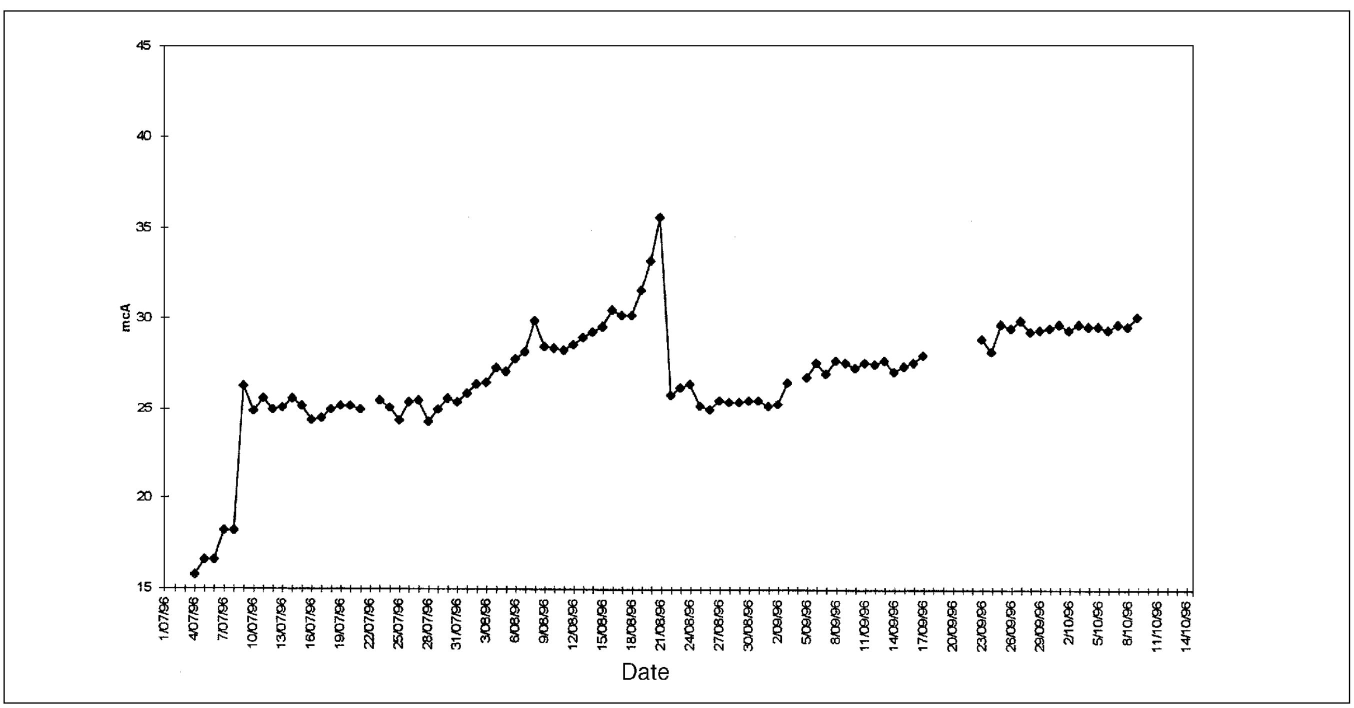

Figure 3 — ***Monitoring ΔP across one stage of an RO plant***

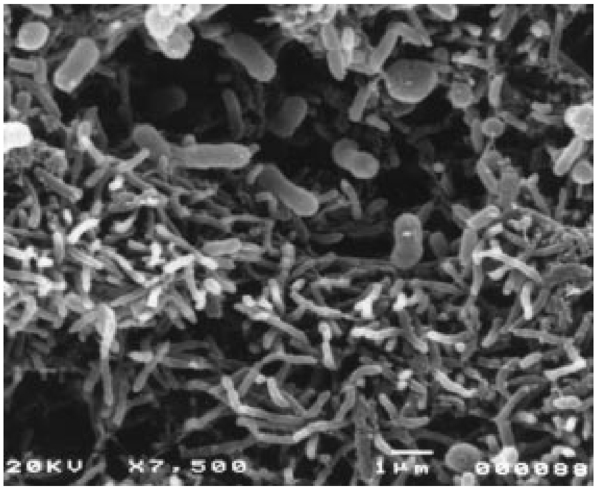

Figure 4 — ***Biofouling of RO membranes (SEM mag X 7,500)***

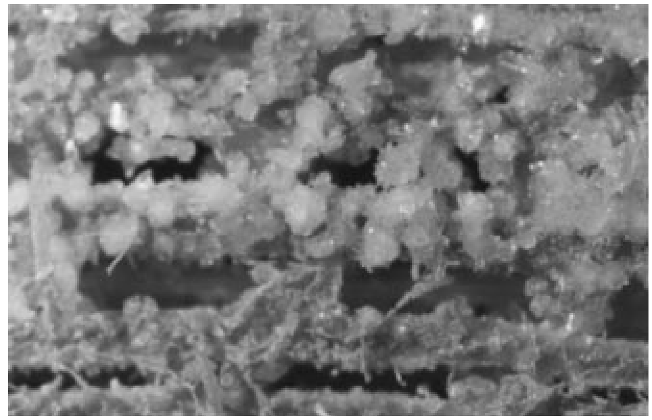

Figure 5 — ***Scaling of RO membranes (calcium phosphate scale)***

Table 1 — ***Common system failures***

Failure	Effect	Recommended Monitoring Practice
Antiscalant	Scale formation on membranes, usually at the back end	Check dosing equipment and monitor changes in water quality, softener failure
Ineffective sanitisation procedures	Biofouled pipework, cartridge filters and membrane	Sand filters, GAC, microbiological analysis, chlorine dosing, dosing tanks
High iron content	Iron loading on cartridge filters	Pipework corrosion, ferric breakthrough from media beds, failure of media filters
High organic content	Humic substances and organic fouling on membrane	Feedwater composition, review flocculation procedures, feedwater colour, TOC
Colloidal breakthrough	Colloidal particles foul micron filters and membranes	SDI, condition of cartridge filters, eliminate media fines
Granular activated carbon filters	Carbon fines foul micron filters and membrane	Check washing procedure to remove fines
Overdosing of flocculant	Cationic flocculant irreversibly fouls membranes	Check dosing levels and detect excess traces
Overdosing chlorine	Membrane damage, high conductivity and increased flux	Dosing equipment, Redox meters, bisulphite dosing levels and positioning of injection point, chlorine test kit
Ineffective biocide	High bacterial and fungal counts in water samples	Biocide adsorption on GAC, check contact time and dose rate, select broad-spectrum biocide
Sand filter breakthrough	Colloidal and bacterial fouling of micron filters and membranes	Check wash procedures to remove fines
Acid dosing	Rapid scale formation, $CaCO_3$ only	pH monitor, plant pressure drop
Seasonal blooms	High microbiological loading, biofilm, severe cartridge filter fouling	Microbiological counts in water samples, evidence of biofilms, check algae counts

Although many of these symptoms are due to failure of the membrane separation process or the dosing equipment, fouling problems are often the result of poor equipment design and inadequate appreciation of the feedwater composition. In addition, plant owners who have operated in trouble-free conditions may increase recovery rates with little understanding of the possible consequences.

Many of the foulants can be removed by cleaning and sanitisation procedures if the foulant build-up is not too severe. However, some pre-treatment failures cause irreversible fouling or permanent membrane damage. The most common membrane damage is due to chlorine, which requires membrane replacement. Another example of severe fouling is the breakthrough of cationic polymeric flocculants that irreversibly react with the negatively charged membrane surface.

The following examples are of plants that suffered from poor pre-treatment design. There are summaries of how the system was improved or the problem eliminated.

PLANT A: BOILER FEEDWATER, ITALY

Problem: Cartridge filters were partially blocked with a gelatinous deposit and had to be replaced every 6 days at a significant cost to the operator.

Reason: System biofouling due to poor plant sanitisation procedures (Figure 6).

Investigation: Chemical and microbiological analysis were carried out on foulants from the cartridge filter that consisted of 95% organic matter, with high bacterial and fungal counts. Biofilm was also observed on the internal walls of the pipework to the membrane up to 3 mm thick.

Recommendations: Regular monitoring of the cartridge filters. A four-step sterilisation programme was used on the pre-treatment system and membranes using a broad-spectrum non-oxidising biocide as well as the addition of an intermittent on-line dosing of biocide every second day. This plant was producing water for a non-potable application.

Outcome: After 5 months operation as recommended, the cartridge filters had no visible evidence of biofouling and no replacement has been necessary.

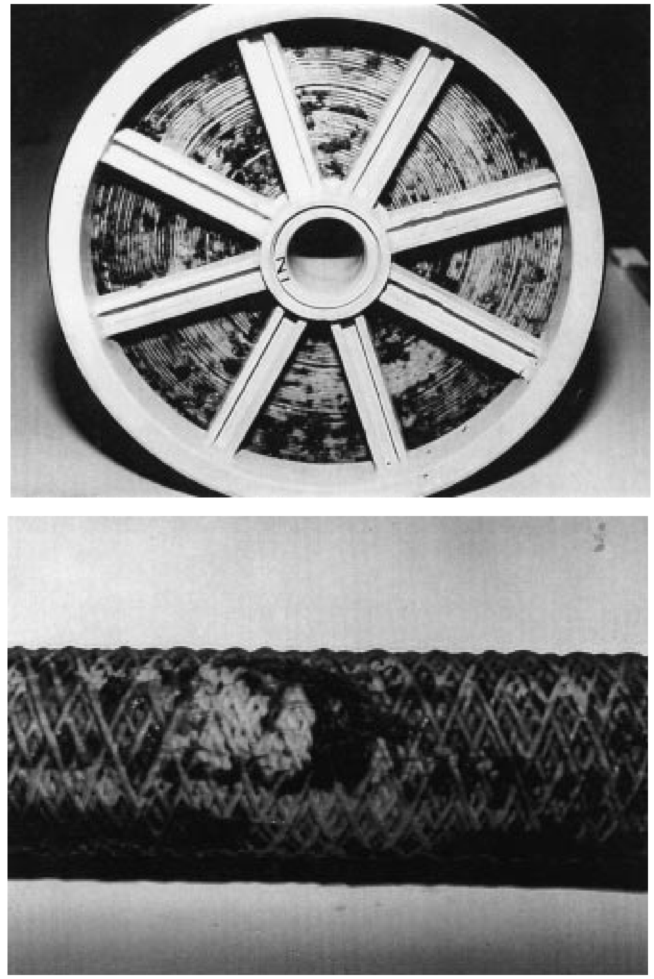

Figure 6 — ***Biofouled membrane (top) and cartridge filter (bottom)***

PLANT B: PROCESS USE FOR A BEVERAGE PLANT, UK

Problem: The RO plant was unable to operate at the required recovery without the risk of calcium carbonate scaling. The use of acid caused severe corrosion problems in the pre-treatment system and heavy iron fouling in the membrane.

Reason: Without pH control, the brine LSI was positive under the specified operating conditions and the plant could not be operated without risk of scale formation.

Investigation: A full water analysis was carried out and an antiscalant prediction programme was used to calculate the brine LSI and determine the antiscalant requirement (Figure 7).

Recommendations: A phosphonate-based antiscalant was recommended at a dose rate of 3.6 mg/l added to the incoming feedwater prior to the cartridge filters to inhibit the formation of inorganic scale and to sequester small traces of dissolved iron.

Outcome: The plant was operated with the required dose rate of antiscalant and no problems of scale formation have been encountered.

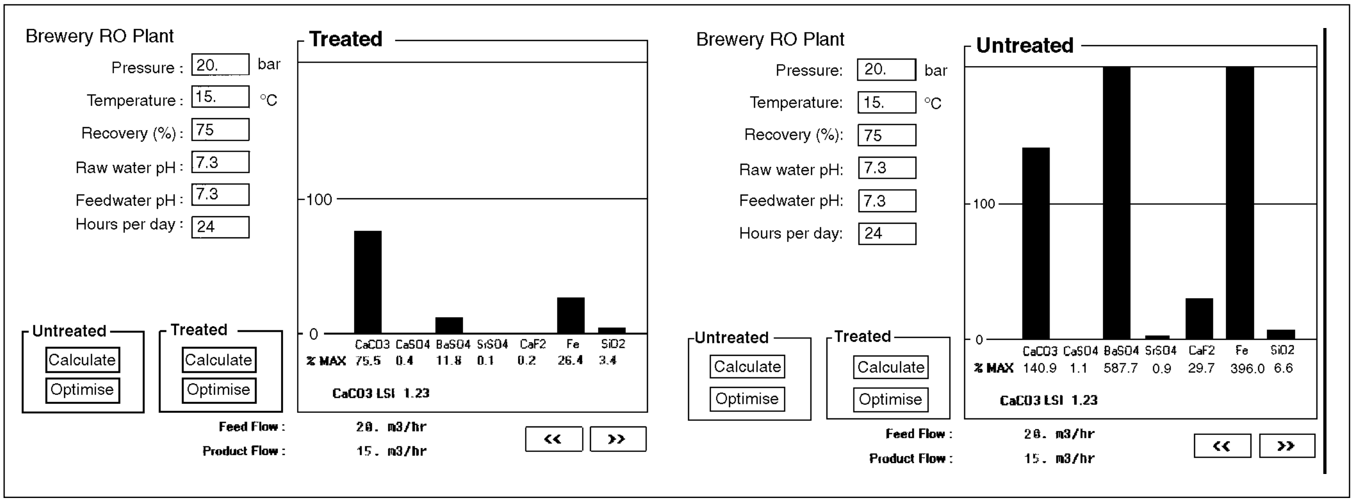

Figure 7 — ***Scaling potential of brine with antiscalant dosing treatment (left) and without treatment (right)***

PLANT C: WATER FOR REACTOR COOLING, EUROPE

Problem: This is a 4,000 m^3/d plant treating surface water. High pressure differentials were observed across the membranes and the cartridge filters were yellow/brown in colour. The plant required cleaning twice a month.

Investigation: A membrane autopsy was carried out and the feedwater analysed. The feedwater contained <0.05 mg/l of total iron, which is a low value. However, analysis of the membrane foulant identified 30% as iron oxide in the dried foulant. It is unlikely that this iron fouling was due to the iron content in the untreated feedwater. The dried foulant also contained 60% of organic matter and 2.96 x 10^8 cfu/cm^2 bacteria.

Reasons: It was suspected that the iron deposits originated from the ferric chloride flocculation and had not been effectively removed by the dual media filters.

Recommendations: It was recommended that the media beds be monitored closely to detect iron breakthrough. The ferric chloride dosing also required optimising. The membrane required cleaning with a weak acid cleaning agent followed by an alkaline surfactant to remove organic material and microorganisms.

Outcome: The plant continued to operate efficiently without further accumulation of iron on the membranes.

CONCLUSIONS

Reverse osmosis for the production of potable and process water is a firmly established practice in the Middle East. Unfortunately, many problems have been reported in the region, often due to biofouling and poor scale inhibition. Many of these situations could be improved by an acceptance for the need to review the design, operation and maintenance of the pre-treatment systems and in some cases consider investment in additional or improved pre-treatment plant.

The key messages to local plant designers, suppliers and owners are:

- Design a pre-treatment plant that is capable of treating the seasonal range of probable feedwaters. The long-term use of a pilot plant can be helpful.
- Select an effective scale and biogrowth control programme tailored for each plant installation and feedwater source. Select programmes based on proven efficacy not lowest price.
- Train all on-site staff in the key parameters and warning signs that indicate forthcoming or occurring plant failure.
- Consider making improvements to the system design to allow individual sections of the pre-treatment to be cleaned in isolation. This is an important issue. Many systems have biofouled pre-treatment systems that cannot be cleaned without a total plant shutdown, which is unacceptable.

- Avoid purchasing the cheapest membrane, plant, system and chemical if it puts the rest of the plant in jeopardy.
- Design cleaning systems that work. Generally, the larger the plant, the more inflexible the cleaning system design. Big plants need large cleaning skids. Using small CIP tanks to save on chemical usage is a false economy.
- Clean fouled plant early in the fouling stage and flush all equipment thoroughly after shutdown and on start-up. Globally, the greatest problem in membrane cleaning is that systems are too badly fouled to begin with.
- Exercise stringent daily monitoring and control procedures.
- Remember, lots of people are doing it worse than you, but some are doing it better. Can you do it better?