

The Impact of Eliminating Softeners as Pretreatment for Reverse Osmosis Systems

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ABSTRACT

Sodium zeolite softeners are often seen as the most efficient method of scale control for reverse osmosis plants and are widely used for pretreatment. This paper looks at the impact on economics and system performance by replacing ion exchange softening with chemical antiscalant.

INTRODUCTION

Controlling the precipitation of sparingly soluble salts has long been an issue with making Reverse Osmosis (RO) technology viable. Scale precipitates on the membrane surface when a soluble salt exceeds its solubility limit in the brine stream of the RO. If some method for preventing scale build-up is not employed, permeate flow and quality are adversely affected. Excessive build-up on the membrane can permanently damage the element and accelerate the need for replacement.

Although common treatment strategies for controlling scale in RO systems include reduced operating recovery and feedwater pH reduction, the two most commonly employed technologies in industrial installations are the use of ion exchange softeners and the use of chemical scale inhibitors. This paper reviews the four primary ways to control scale in RO systems, but focuses on the advantages and disadvantages of ion exchange softening versus chemical scale inhibitors. Two case studies are presented where ion exchange softening was replaced with chemical scale inhibitors as the method to control scale. The economics of this change are discussed with respect to RO system performance.

SCALE

Precipitation of scale occurs when the solubility of a particular salt is exceeded. Scale can be predicted to form by comparing the ion product of the considered salt (I_p) to the solubility product for that salt (K_{sp}) under the same conditions. The ratio of I_p/K_{sp} is the

Saturation Index (SI). Precipitation is predicted to occur when the Saturation Index exceeds 1.0. The ion product, I_p , is defined for salt A_mB_n in Eq. (1). Table 1 lists the solubility constant, K_{sp} for common scales:¹

Equation (1). $I_p = [A]^m * [B]^n$ where [] denotes molar concentration

Table 1—Molar Solubility Product for Common Salts

Salt	K_{sp} Molar Solubility Product
$CaSO_4$	2.5×10^{-5}
$SrSO_4$	6.3×10^{-7}
$BaSO_4$	2.0×10^{-10}
CaF_2	5.0×10^{-11}

In the case of calcium carbonate ($CaCO_3$), the Langelier Saturation Index (LSI) is used to determine if a water is scale forming for water with TDS levels less than 10,000 mg/L. LSI incorporates alkalinity concentration, calcium concentration, pH and temperature. A positive LSI indicates that the water is scale forming. Computer projection software is available that calculates saturation index and LSI based on feedwater characteristics and system operating parameters.

In RO systems, soluble salts found in the feedwater are concentrated in the brine stream due to water being permeated through the membrane. In the boundary layer on the membrane surface, the concentration of salts exceeds that of the bulk water due to the concentration polarization effect. The concentration of ions is as much as 10–20% higher along the membrane surface than in the bulk water. The actual concentration depends upon their rate of diffusion back into the bulk water, which is a function of turbulence in the bulk stream.² Because of this phenomenon, some method of scale prevention should be considered when saturation indices (SI) exceed >0.8 or Langelier Saturation Index (LSI) exceeds –0.2.

REDUCED SYSTEM RECOVERY

One of the most basic ways of preventing scale from forming in RO systems is to operate the process at a lower recovery. Recovery is defined as the permeate flow rate divided by the feedwater flow rate. Decreasing the recovery reduces the concentration of salts in the brine stream. This concentration is determined by multiplying the Concentration Factor (C_f) times the feedwater concentration. The relationship between concentration factor and Recovery (R) is demonstrated in Eq. (2).

Equation (2). $C_f = 1/(1 - R)$

Table 2 shows the effect that system recovery has on concentration factor and on calcium levels in the brine stream for a 100 gpm feedwater containing 100 mg/L of calcium. If a particular ion is determined to be a problem at a specific system recovery, a lower recovery can be selected that limits its concentration in the brine stream in order to prevent precipitation.

The impact of operating a system at lower recovery is to produce less permeate and more brine. This inefficient method of scale control increases the RO's operating cost. Feedwater preparation costs, electricity and wastewater disposal costs add up to make the penalty for lower system recovery significant. Generally, most industrial RO systems are designed at 75% recovery. This is still conservative depending upon the method of scale control employed.

REDUCED FEEDWATER pH

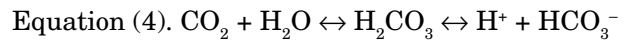
For most natural sources of water, calcium and carbonate are in equilibrium as described in Eq. (3).



Reducing pH, by adding a source of H^+ to the feedwater (i.e., adding acid), shifts this equilibrium to the left keeping calcium ions in solution. Typically, sulfuric acid or hydrochloric acid is used. This simple treatment strategy is effective for carbonate scale only.

When using acid, consideration must be given to the impact that reduced pH has on the solubility of other ions found in the feedwater such as silica. Use of sulfuric acid may also cause a potential problem with sulfate scale (e.g., calcium sulfate, barium sulfate, strontium sulfate) due to the additional sulfate ions contributed by the acid.

Reducing feedwater pH also has an impact on permeate water quality that needs to be considered. As pH is reduced below 8.2, bicarbonate alkalinity (HCO_3^-) is converted to carbonic acid (H_2CO_3) which dissociates into carbon dioxide (CO_2). Eq. (4) shows this relationship.



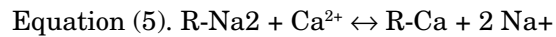
Carbon dioxide, a dissolved gas, passes through the membrane into the permeate stream. Depending upon the level of alkalinity in the feedwater, the impact on permeate quality can be significant, leading to the need for further treatment to improve its quality.

The economics of feeding acid involve the cost of acid. Food grade acid must be used to prevent fouling of the membrane from contaminants found in lesser grades of acid. The dosage of acid is determined by the pH and alkalinity level of the brine stream. Significant levels of alkalinity may result in the need for additional treatment to remove carbon dioxide.

System performance and permeate quality may be acceptable with relatively low pH and alkalinity feedwater sources. Higher pH and alkalinity feedwaters will require greater amounts of acid to prevent carbonate scale, increasing the cost of the treatment while decreasing the quality of the permeate produced.

ION EXCHANGE SOFTENING

Removing hardness from RO feedwater through ion exchange softening has become a common practice in RO pretreatment. Ion exchange technology, unlike reverse osmosis, does not remove dissolved solids from water, rather it is a process that replaces unwanted ions with more desirable ions. See Eq. (5).³



This process is reversible and uses a synthetic resin as the medium to carry out the exchange. After the resin has become saturated with the unwanted ions, it is regenerated by washing it with a solution of the desired ion. The simplest form of ion exchange technology used is the sodium exchanger, which is regenerated with sodium chloride (NaCl). This process softens water by exchanging calcium and magnesium ions with sodium ions.

Table 2 — Concentration Factor versus System Recovery for 100 gpm feedwater containing 100 mg/L Ca

Recovery R%	Conc. Factor (C_f)	Permeate Flow	Brine Stream Flow	[Ca ⁺⁺] in the Stream
0 (Feedwater)	1	0	100	100
10	1.11	10	90	111
20	1.25	20	80	125
30	1.43	30	70	143
40	1.67	40	60	167
50	2.00	50	50	200
60	2.50	60	40	250
70	3.33	70	30	333
75	4.00	75	25	400
80	5.00	80	20	500
90	10.00	90	10	1,000

Conventional ion exchange softening systems are made up of a vessel containing a fixed bed of resin which is regenerated in a cocurrent basis, meaning the water to be treated and the regeneration solution are passed in the same direction, from the top to the bottom of the vessel. Feedwater enters the vessel, where calcium, magnesium and other cations for which the resin has a greater affinity are exchanged for sodium ions. When the effluent hardness concentration exceeds a predetermined level, the unit is taken off-line and regenerated. The complete cycle of exchange is comprised of 5 steps:

Service: (production) The unit is producing water of the desired quality.

Back-washing: (loosening) Water flows in the reverse direction of service to remove any particulate matter or debris that has entered the system.

Regeneration: (chemical injection) Diluted regenerant is passed in the direction of service (cocurrent) through the bed to restore the capacity of sodium ions.

Displacement rinse: (slow rinse) Water is used to push out the remaining regenerate solution from the vessel.

Fast Rinse: Water is introduced at the service rate of flow until the desired quality of produced water is achieved.

Although scale is the primary reason for using an ion exchanger softener, these units are often installed as sacrificial filters to trap particulate matter, including iron, to prevent it from entering the RO system. Additionally they are sometimes installed to remove residual cationic polymers, which may pass through a poorly maintained upstream media filter. Ion exchange resins are not intended to fill these roles and perform poorly in doing so. When used for purposes other than ion exchange, operation and maintenance costs of this unit process increase significantly.

As with any unit process, there is a cost associated with purchasing, installing and operating an ion exchange unit. Most often, it is only the capitalized costs of the ion exchange unit that is reviewed when making the installation decision. Operating cost, usually not calculated and assumed to be negligible, is often ignored and can be significant. The total operating costs of a softener include:

Salt Cost: A function of total feedwater hardness, desired hardness output and regeneration efficiency

Water Costs: Includes the costs of treatment (pre and post) for water used to regenerate the unit which is wasted

Electricity: Incremental pumping cost to overcome system pressure drop

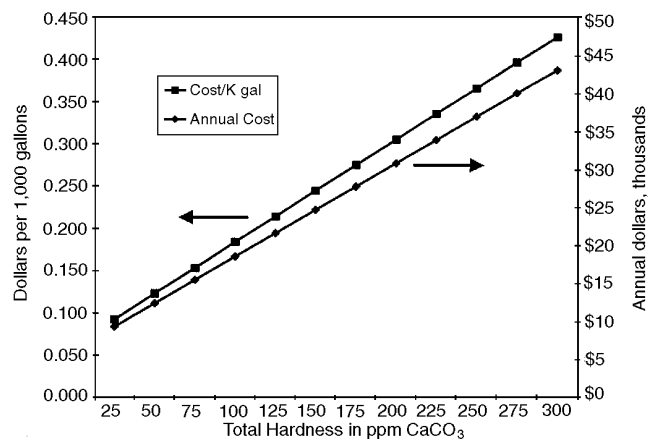


Figure 1 — Operating Cost for a 200 gpm Ion Exchange Softener

Labor: Dedicated to testing, regenerating, receiving salt and performing system maintenance

Maintenance: Includes resin replacement and general maintenance items

The most significant cost for operating an ion exchange softener is that of salt, which is most directly impacted by, and is linear in relationship to the feedwater hardness. Disposal cost can be significant in some cases, particularly if the resin is regenerated in the hydrogen form. Figure 1 shows the total annual cost and cost per 1,000 gallons for operating a 200-gpm softener at hardness levels from 25 to 300 ppm as CaCO₃ regenerated with sodium chloride. The basis for this calculation appears in Table 3.

Table 3 — Basis of calculations for Figure 1

Item	Basis
Salt Cost	\$65 / Ton
Electricity	\$0.070 / kW Hour
Labor	\$50 hr
Labor Hours	2 hr /wk
Resin Replacement Cost	\$30/ft ³ (10% annual replacement)
Water Cost	\$2.00 / kgal
Waste Water	\$1.00 / kgal
Resin Volume	100 ft ³
# NaCl / ft ³	10.0
Pump Efficiency	80%
Motor Efficiency	95%
Pressure Drop	10 psi
Regeneration Volume	190 (gal cycle)
Back Wash Volume	750 (gal cycle)
Rinse Water	5000 (gal cycle)

CHEMICAL SCALE INHIBITORS

A final alternative to retarding scale formation in RO systems is the use of scale inhibitors. These chemicals function by one or more closely related mechanisms, which interfere with or disrupt the crystal growth stages.

Threshold Effect: Causes a delay in precipitation by the application of sub-stoichiometric amounts of chemical inhibitor which adsorbs onto the surface of the incipient precipitate.⁴ Threshold inhibitors include polyphosphates, organophosphorous compounds, and polymers.

Crystal Distortion Effect: Normal crystal growth is modified by the inhibitor. This produces an irregular crystal structure with poor scale forming ability.

Dispersancy Effect: The inhibitor places an electrostatic surface charge on the forming crystal, causing a mutual repulsion. Organic dispersants include organophosphorous compounds and polyelectrolytes.⁵

The first scale inhibitor widely used was sodium hexametaphosphate [(NaPO₄)₆] or SHMP. Although still used, SHMP has lost market share to more cost-effective scale inhibitors. Phosphonates, as identified by the stable C-P bond, overcome the tendency to hydrolyze the O-P chain, which is typical of polyphosphates such as SHMP. Numerous polymers are commercially available. The most common is polyacrylic acid [CH₂CHCOOH]_n with molecular weights in the range of 1,500 to 2,500.

The economics of scale inhibitors are based on the nature of the inhibitor, scale conditions in the brine stream and the operating recovery of the RO system. The most effective are threshold inhibitors, which use sub-stoichiometric amounts of treatment. The amount of inhibitor is usually in the range of 1 to 5 mg/L even in the treatment of very hard waters.

CASE STUDIES

The economics of capital and operating costs versus system performance are important issues in consid-

ering what type of RO pretreatment to use. The following two case studies show the impact on operating cost versus performance of two existing RO plants that converted from ion exchange softening to chemical scale inhibitors.

CASE STUDY #1 — A microelectronics plant in California commissioned an RO system in 1985. Key features of the water system are:

Raw water source:	City
Permeate use:	Rinse water for hard drive disk manufacture
Membranes:	Polyamide, spiral wound
Output:	120 gpm
Recovery:	75%
Array:	4:2
Ion Exchange Softeners:	2 x 40 ft ³ resin regenerated with sodium chloride
Water analysis:	Variable. Table 4 shows the analysis used for design.
Water System:	Refer to Figure 2.

Previous Operation — Plant used two 40 ft³ ion exchange softeners to control scale in the RO system. Figure 3 shows a computer projection for the calculated saturation index and LSI for the raw water based on the systems 75% recovery. By using ion exchange to soften the water, scale potential was minimized.

After several years of operation, the softeners were in need of significant repair. Softener laterals were broken that regularly allowed resin beads to break through and foul down stream cartridge filters in front of the RO. Estimates for repair were \$25,000. A resin analysis determined that it needed to be replaced at an estimated cost of \$6,400. A thorough system survey determined the following additional information:

Annual Salt Cost:	\$24,000 per year for regeneration
Annual Water Cost:	\$11,600 per year for system regeneration
Electrical Pumping Cost:	\$1,100 per year (additional) to overcome the vessel pressure drop.

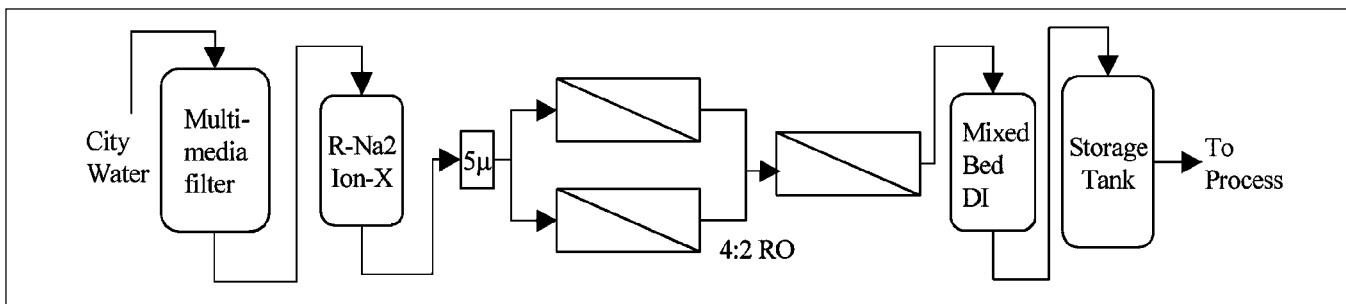


Figure 2 — Flow Diagram for Case Study #1

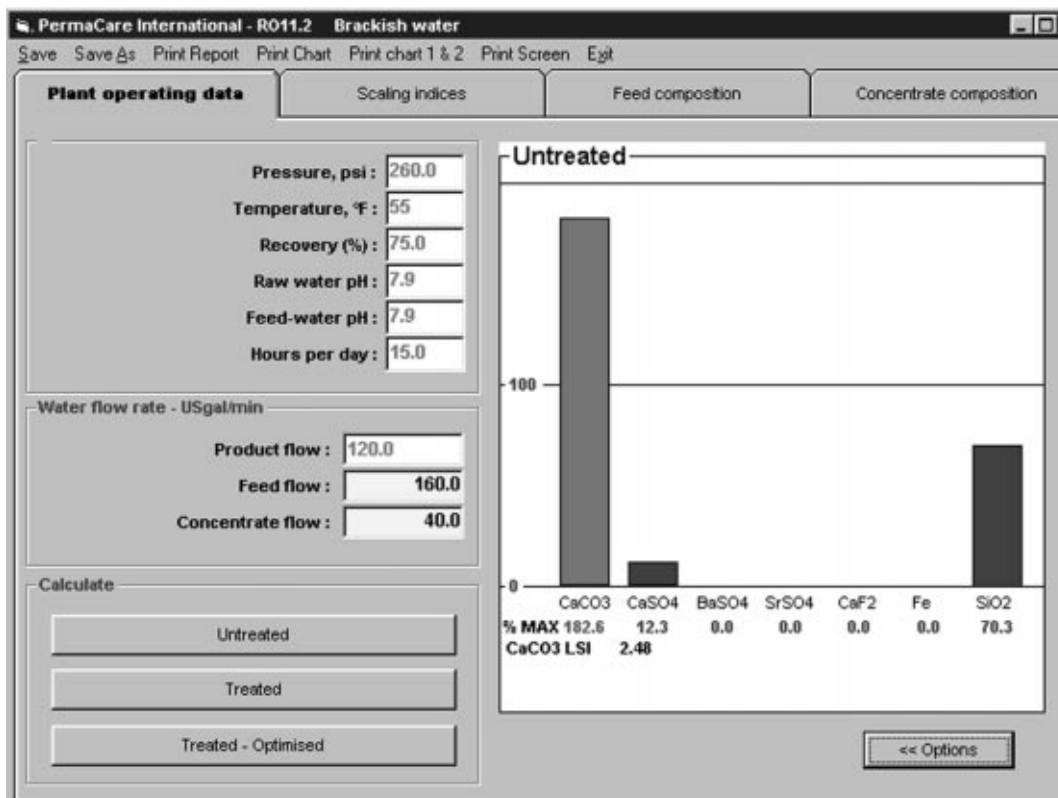


Figure 3 — Projection of Solubility Indices and LSI for Case #1⁶

Labor Cost: \$11,700 per year for maintaining softeners and handling salt delivery

System Performance: Membranes cleaned on average every 10 months due to a decrease in permeate flow

RO Operations: 14–16 hours/day

Table 4 — Case Study Water Analysis

Ion	Case #1 (mg/L as ion)	Case #2 (mg/L as ion)
Ca	150	60
Mg	57	30
Na	98	36
K	3.4	n/a
SO ₄	118	60
Cl ⁻	251	90
HCO ₃	375	180
NO ₃	24	19
SiO ₂	25	9
pH	7.9	7.8
LSI (brine)	2.48	1.83

Current Operation — Due to the need for capital expenditure to re-build or replace the softeners, it was decided to replace them with a chemical scale inhibi-

tor. A threshold scale inhibitor was used to control scale in the RO system. Because the system does not operate continuously, a feedwater flush system needed to be installed to remove concentrated salts from the RO prior to shutting it down. The cost of this installation was \$500. Additional costs were:

Annual Scale Inhibitor
 Cost: \$8,000 per year
 Dosing Pump: \$700
 Labor: \$1300 per year to take delivery and make up scale inhibitor

System Performance: Membranes were cleaned after 11 months due to a decrease in permeate flow as routine

Summary — Performance of RO was unchanged. Salt rejection, permeate flow, feed/differential pressures remained consistent with previous performance. An annualized savings of \$39,100 (\$24,000 + 11,600 + 1,100 + 11,700 – 8,000 – 1,300) in operating costs were realized. Savings due to capital avoidance of \$30,200 (\$25,000 + 6,400 – 500 – 700) were realized. The Return on \$1,200 Investment (ROI) exceeded 3150% [100% * (\$39,100 – 1200)/1200].

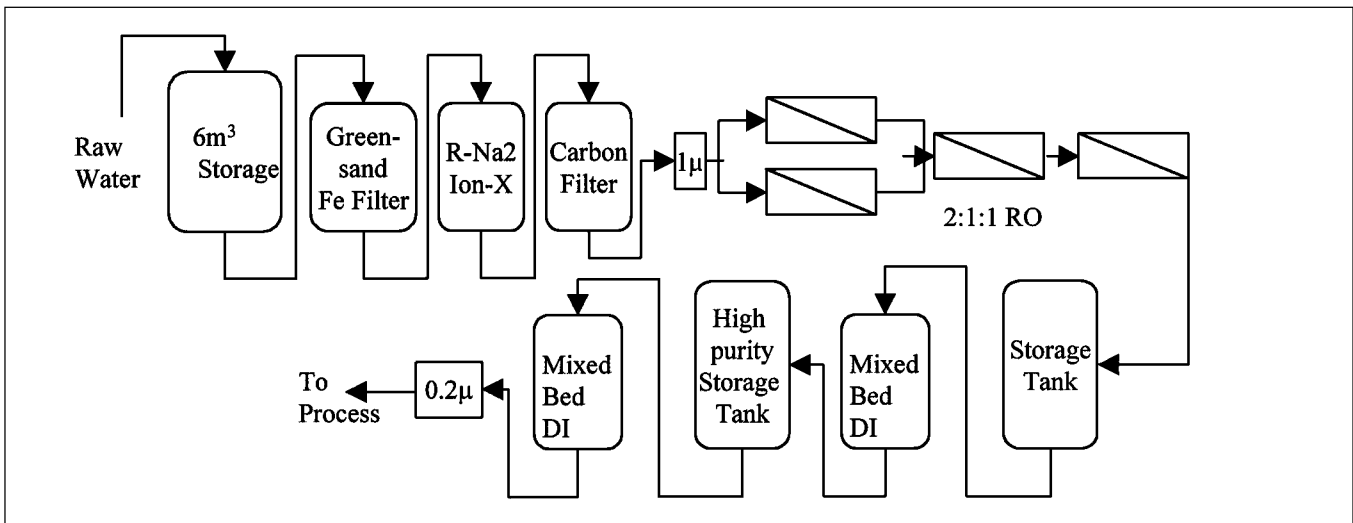


Figure 4 — Flow Diagram for Case Study #2

CASE STUDY #2 — A semi-conductor plant in the United Kingdom commissioned an RO system in 1990. Key factors for this water system are:

Raw water source: City
 Permeate use: Rinse water for hard drive disk manufacture
 Membranes: Polyamide, spiral wound
 Output: 480m³/day (75 gpm)
 Recovery: 75%
 Array: 2:1:1
 Ion Exchange Softeners: Resin regenerated with sodium chloride
 Water analysis : Variable. Table 4 shows the analysis used for design.
 Water System: Refer to Figure 4.

Previous Operation — The plant used an ion exchange softener with an estimated bed volume of 1.3 m³ (46 ft³) to control scale in its RO system. Figure 5 shows a computer projection for the calculated saturation index and LSI for the raw water based on 75% recovery.

The ion exchange softener was being operated beyond its design capacity in order to provide sufficient feed-water for the RO. Installation of a replacement softener was estimated at \$15,000 (£10,000)⁸. Plant engineers were tasked by management to reduce costs in their area. A thorough system survey determined the following additional information:

Annual Salt Cost: \$13,800 (£9,200) per year for regeneration
 Annual Water Costs: \$1,342 (£895) per year for system regeneration
 Electrical Cost: \$337 (£225) per year (additional) to overcome vessel pressure drop

Labor Costs: \$3,168 (£2,112) per year for maintaining softeners and handling salt
 System Performance: Membrane cleaning not necessary due to operating performance
 RO Operations: Plant runs on average 16–18 hours/day. RO had an auto-flush system.

Due to the need to avoid capital expenditure to replace the softener and to reduce plant-operating costs, it was decided to replace the ion exchange softener with a chemical scale inhibitor.

Current Operation — A threshold scale inhibitor is used to control scale in the RO system. Because the RO had a pre-existing auto-flush system to prevent concentrate reject standing in the membranes during prolonged downtime, no investment was required. Key factors:

Annual Scale Inhibitor Cost: \$3,900 (£2,600) per year
 Dosing Pump: \$600 (£400) includes a day tank
 Annual Labor Costs: \$1500 (£1000) per year to take delivery and make up scale inhibitor
 System Performance: After two years of operation, the membranes have not required cleaning.

Summary — Performance of the RO system has been unchanged since replacing the ion exchange system with a chemical scale inhibitor. Salt rejection, permeate flow and feed/differential pressures remained consistent with past performance. The system has gone over 2 years without requiring the membranes

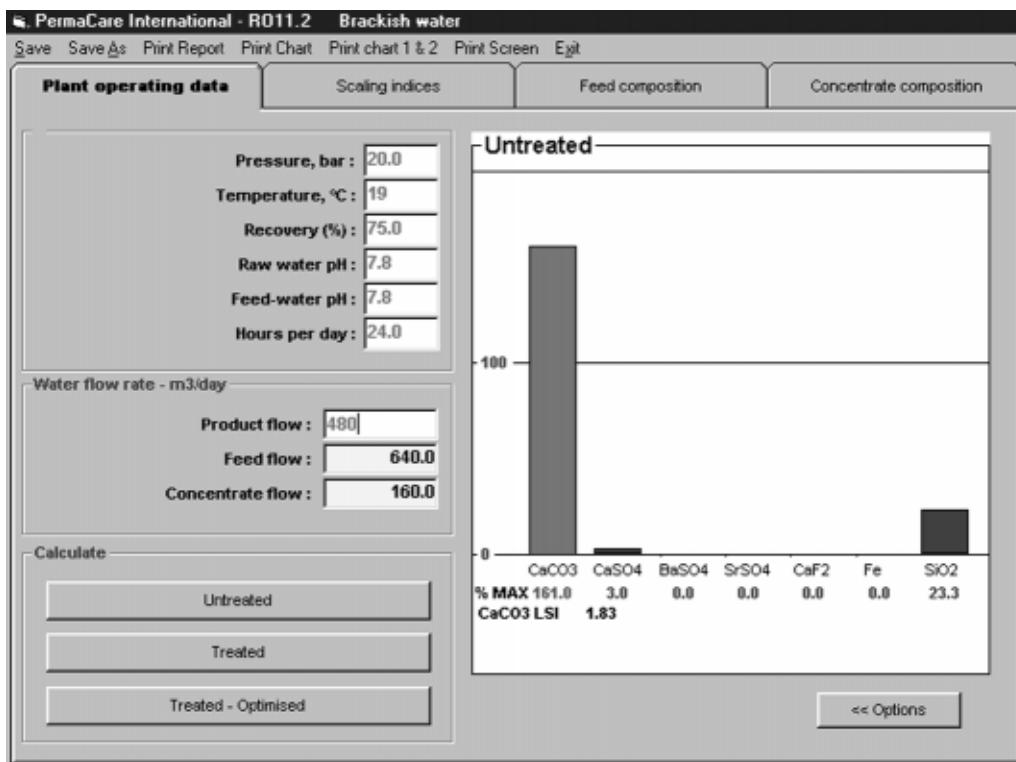


Figure 5 — Projection of Solubility Indices & LSI for Case #27

to be cleaned. Savings in total annualized operating costs of \$13,247 [\$13,800 + 1,342 + 337 + 3,168 – 3,900 – 1,500] (£8,832) are recognized. Additional savings of \$14,400 [15,000 – 600] (£9,600) in capital avoidance were recognized. The Return on the \$600 (£400) Investment (ROI) exceeded 2,100% [$100\% * (\$13,247 - 600)/600$].

CONCLUSION

Applying some method of scale control improves the economic viability of RO systems. Although there are four common ways to control scale in an RO, the most commonly employed technologies for industrial installations are the use of ion exchange softeners and chemical scale inhibitors. This paper discussed these technologies and presented two case studies that demonstrated capital costs avoidance as well as lower operating costs by replacing existing ion exchange softeners with chemical scale inhibitors. Savings were shown to be significant even for low flow rate systems. The amount of expected savings increases with feedwater hardness due to the direct, linear cost relationship of ion exchange softeners versus the substoichiometric dosage requirements of chemical scale inhibitors. The paper concludes that there can be considerable savings in operating costs by replacing softeners with scale inhibitor.

Although rather inefficient and expensive, ion exchange resin will serve as a sacrificial filter helping

to remove particulate matter and residual coagulants. Lower overall cost and improved system performance would be achieved by installing a filter that uses a proper medium for reducing the fouling potential of the RO feedwater. A concern with using scale inhibitors that needs to be addressed is the setting up of safeguards, through either monitoring or automation, that insure the correct, prescribed amount of inhibitor to control scale is present in the feed/reject water at all times. Overcoming this issue will allow the confident use of chemical scale inhibitors to safely control scale and to improve the economic performance of RO systems.

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8. Exchange rate 1£ = \$1.50 US

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