Aquaporin Inside®

Industrial Reverse Osmosis Membrane Elements

Technical Manual

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Introduction

Reverse osmosis (RO) membranes are commonly used in engineering systems for product stream concentration or purification, wastewater treatment and recycling, and desalinations. Aquaporin Inside® Industrial RO Membrane Elements are biomimetic membrane elements which incorporate functional aquaporin proteins. Aquaporins are water channel proteins that are found in all living organisms, from plants to human bodies, where they are responsible for rapid water transportation across cell membranes. Aquaporin Inside® membranes harness nature's capability for selective molecule transport by mimicking cell membranes with aquaporin proteins embedded and stabilized.

Proper handling, operation, and maintenance of Aquaporin Inside® Industrial RO Membrane Elements and the systems in which they are installed are key factors in maximizing the long-term system availability and efficiency. These key factors must be considered starting from the design phase and throughout the manufacturing, construction, and commissioning of the system. Likewise, RO membranes require specialised care to maintain their performance over the long term.

This user manual covers the essential guidelines for the handling and storage, operation, maintenance, and troubleshooting of the Aquaporin Inside® Industrial RO Membrane Elements so as to maximize membrane efficiency and facilitate the successful operation of the RO membrane system.

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System Operation

2.1 Introduction

For the successful long-term performance of an RO membrane system, proper procedures for before, after, and during the operation of the system shall be followed. These include feed water quality control, system operation parameter design, element loading, RO system start-up and shutdown, and so on. Preventing fouling, scaling, plugging and membrane degradation should be of highest priority when designing the system, as well as during commissioning and operation.

This section offers the recommended guidelines for system operation procedures and precautions to facilitate good long-term performance of the membrane system, and the membrane elements.

As the specifications and operational ranges vary between each specific model, please also refer to the datasheet of your model when studying the contents and guidelines in this manual.

2.2 Feed Water Quality and Pretreatment

The lifetime and efficiency of reverse osmosis (RO) elements are strongly dependent on adequate and effective pretreatment of the feed water. Pretreatment steps include processes that avoid or minimize fouling, scaling, membrane degradation, and damage. The necessary and adequate pretreatment steps are highly determined by the feed water source, feed water composition, and application. An overview of important feed water parameters, common foulants and scale-forming sparingly soluble salts are given below, as well as the steps required to prevent premature membrane failure.

2.2.1 Important Feed Parameter Guidelines

- Turbidity expresses the degree of cloudiness of the feed water and is an indicator of its fouling potential. It is measured in nephelometric turbidity units (NTU). The maximum allowable turbidity of feed water is 1 NTU.
- The silt density index (SDI), also referred to as the fouling index (FI), is another indicator of a feed water's fouling potential. It is measured by the plugging rate of a defined filter during a defined period at a defined pressure. The maximum allowable 15-minute SDI of feed water is 5.
- Oil and grease can adsorb onto the RO membrane surface if present in the feed water. The detrimental effects of oil and grease on RO membranes are dependent on the chemical nature of these organic substances (saturated, unsaturated, aromatic, or aliphatic) and are also largely dependent on the existence of functional groups. The maximum allowable oil and grease concentration is 0.1 mg/L.
- Total organic carbon (TOC) and chemical oxygen demand (COD) are two parameters used to quantify the organic load in the feed water. High organic content will lead to an increase of biological and organic fouling of RO membranes. The maximum allowable TOC of feed water is 3 mg/L. The maximum allowable COD is 10 mg/L.
- Free chlorine is a strong oxidizing agent and leads to irreversible damage of RO membranes. Free chlorine can be monitored using oxidation reduction potential (ORP). The ORP at neutral pH should not exceed 300 mV. The maximum allowable free chlorine concentration is 0.1 mg/L.
- Aluminum, manganese, and ferric iron can cause severe fouling on the RO membrane. The maximum

allowable concentration of aluminum, manganese, and ferric iron is 0.5 mg/L, respectively.

2.2.2 Scaling Prevention

Scaling of RO elements may occur if salts are concentrated beyond their solubility limit. Prevention of scaling can be achieved by acid addition, antiscalant addition, softening, preventive cleaning, or adjustments of operational parameters.

1. Acid addition shifts the equilibrium of salts, such as $CaCO_3$, towards their dissolved form by lowering the pH value. Commonly used acids include sulfuric acid and hydrochloric acid. Acid addition only mitigates carbonate scaling.
2. Antiscalant addition mitigates or decelerates the precipitation of sparingly soluble salts by preventing crystal formation. Commonly used antiscalants include sodiumhexametaphostphate, organophosphonates, polyacrylic acids, and other commercial combination products.
3. Softening removes scale-forming cations, such as Ca^{2+} or Mg^{2+}, by exchanging them with mainly Na^{+} cations.
4. Preventive cleaning can be conducted by a simple forward flush at low pressure or by using cleaning chemicals.
5. Adjusting operational parameters can help to avoid precipitation of sparingly soluble salts by ensuring they stay below their solubility limits. This can be achieved by reducing system recovery, increasing the element cross flow rate, increasing the feed temperature, or adjusting the feed pH, depending on the salt.

2.2.3 Colloidal Fouling Prevention

Colloidal fouling of RO elements may occur when suspended or colloidal matter is present in the system. Prevention of colloidal fouling can be achieved by media filtration, oxidation filtration, microfiltration, or ultrafiltration.

1. Media filtration removes suspended or colloidal particles by depositing them on the surface of the filter media grains. Commonly used filter media include sand and anthracite.
2. Oxidation filtration oxidizes ions, such as divalent iron or manganese, which then form insoluble colloidal hydroxides. These are then removed by media filtration. Commonly used oxidizing agents include oxygen or air.
3. Microfiltration and ultrafiltration membranes remove most suspended matter, depending on their pore sizes. Cartridge microfiltration is usually the last step in a pretreatment system and aims to protect the RO membrane and high-pressure pump from suspended solids.

2.2.4 Biological Fouling Prevention

Biological fouling of RO elements may occur if microorganisms, such as bacteria, algae, fungi, or viruses, are present in the feed water and form a biofilm on the membrane surface. Microorganisms can be regarded as colloidal matter and can be removed as explained above. However, unlike non-living matter, microorganisms are able to reproduce if small leakages occur during pretreatment. Prevention of biological fouling can be achieved by chlorination, which inactivates microorganisms (disinfection). After disinfection, the residual free chlorine must be removed completely before it reaches the RO membrane. De-chlorination processes can be found in the membrane degradation prevention section. In some instances, non-oxidizing biocides are used for biological fouling prevention.

2.2.5 Organic Fouling Prevention

Organic fouling of RO elements may occur when organic substances, such as humic substances, proteins, sugars, oils, and greases, adsorb onto the membrane surface. Prevention of organic fouling can be achieved by coagulation, ultrafiltration, or activated carbon.

2.2.6 Prevention of Premature Membrane Degradation

Premature membrane degradation of RO elements may occur from oxidizing agents (including free chlorine added during pretreatment) present in the feed water. Prevention of premature membrane degradation can be achieved by activated carbon prefiltration or chemical reduction of oxidants by dosage of reduction agents, such as sodium metabisulfite.

Table 1: Recommended system design limits and guidelines.

	Feed source				
	RO permeate	**Well water**	**Softened surface water**	**Surface water**	**Secondary wastewater effluent**
Feed SDI (-)	<1	<3	<3	<5	<3
Maximum recovery per element (%)	30	19	17	15	13
Maximum element flux (GFD)	28	23	20	18	16
Maximum element flux (LMH)	48	39	34	31	27
Typical system design flux (GFD)	22	18	16	14	12
Typical system design flux (LMH)	37	30	27	24	21
Element type	**Max. permeate flow rate per element in GPD (m^3/h)**				
4040	2400 (0.38)	2000 (0.32)	1700 (0.27)	1500 (0.24)	1400 (0.22)
4040XL	2600 (0.41)	2100 (0.33)	1800 (0.28)	1600 (0.25)	1500 (0.24)
8040-400	11200 (1.77)	9200 (1.45)	8000 (1.26)	7200 (1.14)	6400 (1.01)
8040-440	12400 (1.96)	10200 (1.61)	8800 (1.39)	8000 (1.26)	7100 (1.12)
Element type	**Max. feed flow rate per element in GPM (m^3/h)**				
4040	16 (3.6)	16 (3.6)	15 (3.4)	14 (3.2)	13 (3.0)
4040XL	16 (3.6)	16 (3.6)	15 (3.4)	14 (3.2)	13 (3.0)
8040-400	75 (17)	75 (17)	73 (17)	67 (15)	61 (14)
8040-440	75 (17)	75 (17)	73 (17)	67 (15)	61 (14)
Element type	**Min. concentrate flow rate per element in GPM (m^3/h)**				
4040	2 (0.5)	3 (0.7)	3 (0.7)	4 (0.9)	5 (1.1)
4040XL	2 (0.5)	3 (0.7)	3 (0.7)	4 (0.9)	5 (1.1)
8040-400	10 (2.3)	13 (3.0)	13 (3.0)	15 (3.4)	18 (4.1)
8040-440	10 (2.3)	13 (3.0)	13 (3.0)	15 (3.4)	18 (4.1)

Important note: Please consult the chemical supplier before determining the dosing rate and concentration of any chemical. Over-dosing may result in adverse effects, including membrane scaling, fouling, and degradation. For cleaning instructions, please refer to the "Cleaning" section (Section 3).

2.3 RO System Design

The feed water source and quality have a significant impact on RO system design due to its tendency to cause fouling and scaling. For example, feed water of high quality, such as an RO permeate with an SDI of less than 1, has significantly lower fouling potential than surface water with an SDI of 5. Hence, the average typical flux that a system is designed for is highly dependent on the water source. Other important parameters that need to be accounted for in the system design include the maximum recovery rate, maximum permeate flow rate, maximum feed flow rate, and minimum concentrate flow rate per element. **Table 1** lists the recommended system design limits and guidelines as functions of feed water source quality.

2.4 Element Loading

2.4.1 Pressure Vessel Preparation

To prevent dust, debris, or other matter damaging the RO membrane, pressure vessels must be thoroughly cleaned prior to RO element loading. Freshwater rinsing is not sufficient to clean the vessel. It is recommended to use a sponge ball wrapped in a cloth or towel and soaked in a 50% glycerin solution. The sponge ball can be attached to a rope and either pushed or pulled through the vessel. Ensure that the inside of the vessel is not scratched or damaged during cleaning. Make sure that the end caps from both sides are also thoroughly washed.

2.4.2 Loading of RO Elements

The following steps should be followed when loading RO elements:

1. RO elements are loaded with the brine seal facing the upstream direction (**Figure 1**). It is good practice to load elements from the feed side, so the first element loaded is the lag/tail element and the last element loaded is the lead element. During the process, it is recommended to keep the RO elements in their plastic bags until they are loaded. Make sure to maintain a loading record of each element's serial number, vessel location, and position.
2. Gently insert the first element two-thirds of its length into the vessel (**Figure 2**). Lubricate the brine seal thoroughly, using glycerin or silicon-based lubricants. Make sure that the brine seal sits properly in the seal groove on the anti-telescoping device.
3. Lubricate the interconnector O-rings and slide the interconnector into the permeate tube of the lag/tail RO element (**Figure 3**). Lift the next element and install the trailing end on the interconnector while holding the previous element in place (**Figure 4**).
4. Push the elements into the pressure vessel until two-thirds of the trailing element are inserted.
5. Repeat the above steps until all elements are loaded.
6. Once the last element has been loaded, make sure that the lag/tail element fully connects with the end plate permeate adaptor on the brine side of the pressure vessel.
7. If available, make sure that thrust support cones are installed between the pressure vessel end cap and the last element to support it in case of telescoping.
8. Pressure vessel dimensions may vary between vessel manufacturers due to different tolerances and to account for differences in RO element

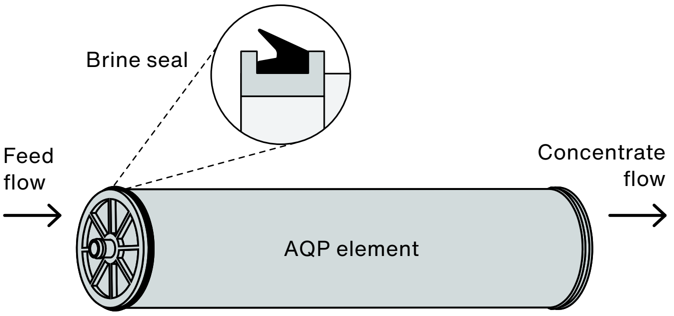

Figure 1: Orientation of brine seal.

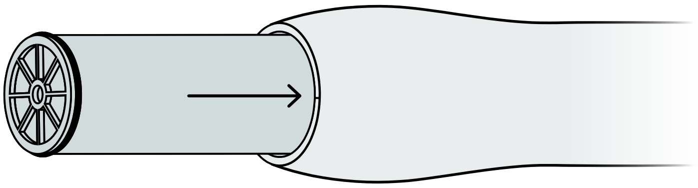

Figure 2: Insertion of first RO element.

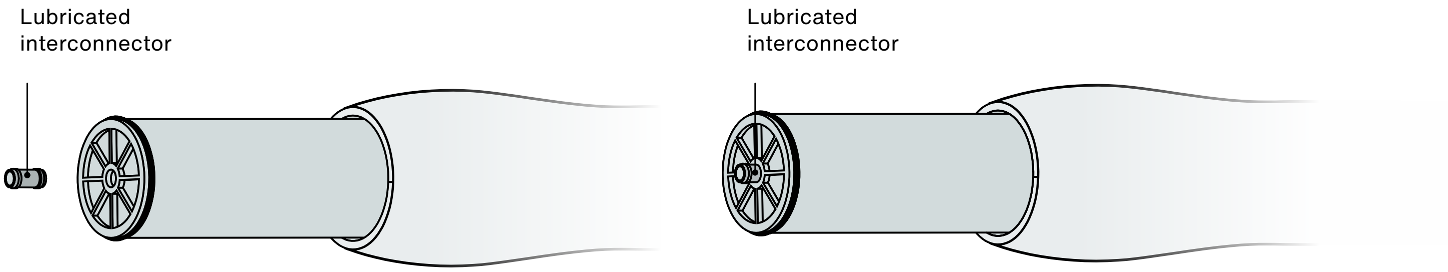

Figure 3: Installation of lubricated interconnector.

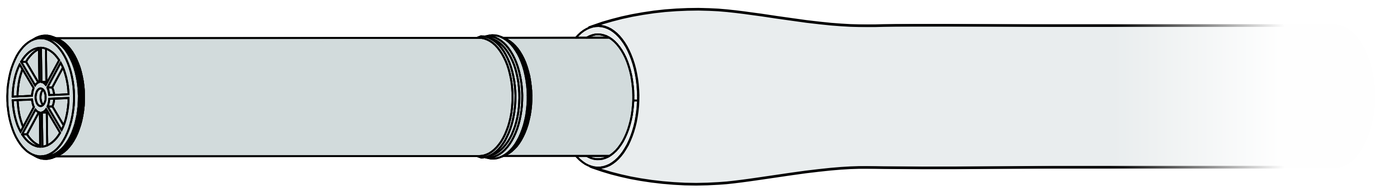

Figure 4: Insertion of next RO element.

lengths. It is therefore recommended to add shims on the feed end of the lead element loaded to prevent excessive movement of the element stack. This helps to avoid leaks in between elements and prevents the interconnector from uncoupling.

9. Pressure vessels and RO elements should be flushed soon after loading to avoid pressure vessel corrosion from RO element preservatives.

2.5 System Start-up and Shutdown

2.5.1 System Commissioning

Before system commissioning, ensure that the feed water quality matches RO element requirements. In particular, the following items need to be stable: flow, SDI, turbidity, temperature, pH, TDS, residual chlorine, and bacteria count.

The following parts of the RO system should undergo mechanical inspection before initial start-up:

- Media filters and cartridge filters
- Feed, concentrate, and permeates lines and valves
- Chemical addition lines and valves
- Chemical mixing in the feed stream
- RO system safety shut-off
- Pressure relief protection
- Complete chlorine removal
- Instrumentation for pretreatment and operational monitoring

The following sequence is recommended when starting the initial operation:

1. Thoroughly rinse the pretreatment section to flush out residuals and other contaminants without allowing the feed to enter the RO elements.
2. Make sure that all valve settings are correct. The feed pressure control valve and concentrate control valve should be fully open. The concentrate valve can be used to carefully make recovery adjustments once the system is up and running.
3. Flush the RO elements and pressure vessels, preferably with permeate water or high-quality feed water.
4. Use low flow rates at first to expel the air out of the RO elements and the pressure vessels at pressures of 30 - 60 psi (2 - 4 bar) for more than 30 minutes. RO systems must be pressurized at a controlled rate of no more than 10 psi (0.69 bar) per second. If pressurization is too rapid, mechanical damage will occur to the RO membrane, including cracking of the wrapping and telescoping of the element. At all times, the maximum allowed pressure drop is 15 psi (1 bar) per element and 60 psi (4 bar) per vessel.
5. All permeate and concentrate flows should be drained during flushing. At this point, all pipe connections and valves should be checked for leaks.
6. After the system has been flushed, close the feed pressure control valve, making sure that the concentrate control valve stays fully open.

7. Open the feed pressure control valve incrementally so that feed pressure does not exceed 60 psi (4 bar). Then start the high-pressure pump.
8. Increase the feed pressure and feed flow rate to the elements until the design concentrate flow is reached, without exceeding a pressure increase of 10 psi (0.69 bar) per second. Then slowly close the concentrate control valve until the ratio of permeate flow to concentrate flow approaches the designed recovery ratio.
9. Keep opening the feed pressure control valve and closing the concentrate control valve until the design permeate and concentrate flows are obtained, while checking the system pressure to ensure that it does not exceed the upper design limit.
10. After adjusting the two valves, calculate the system recovery and compare it to the system design value.
11. Check chemical additions of acid, antiscalant, and sodium metabisulfite. Check pH and conductivity.
12. After allowing the system to run for 1 hour, take the first reading of all operating parameters. Read the permeate conductivity from each pressure vessel and identify vessels with any malfunction.
13. After 24-48 hours of operation, record all plant performance data, such as feed pressure, pressure drop, temperature, flows, recovery ratio, conductivity, pH, and ORP. Take samples of the feed water, concentrate, and permeate water and analyze their constituents. Compare system performance to design values. Use the initial system performance information as a reference for evaluating future system performance. Measure system performance regularly during the first week of operation.

2.5.2 Regular Start-up Procedures

After system commissioning, the following procedures should be followed each time the system is started up:

1. Check the feed water quality meets recommendations for the RO elements used.
2. Flush the RO system with pre-treated feed water at low feed pressure prior to starting the high-pressure pump.
3. Ensure the regulating valve between the high-pressure pump and RO elements is nearly closed during start-up to avoid water hammer.
4. Gradually increase the feed pressure and feed flow rate to the RO elements while throttling concentrate flow rate. Avoid excessive flow rates and differential pressures across pressure vessels during start-up. At all times, the maximum pressure drop is 15 psi (1 bar) per element and 60 psi (4 bar) per vessel.
5. Adjust the RO operating parameters to the targeted permeate and concentrate flow rates. Do not exceed design recovery during any stage of operation.
6. Drain the permeate until the required water quality is obtained.

2.5.3 System Shutdown Considerations

The following actions should be performed when the system is shutdown:

1. Flush the concentrate during RO system shutdown with permeate water or high-quality feed water at low pressure to completely remove high salt concentrations from pressure vessels.
2. Ensure that no pretreatment chemicals are present in the water used for flushing, especially no antiscalants.
3. Ensure all membrane elements are kept wet and properly sterilized and/or frost-protected at all times during shutdowns. If the plant is stopped for longer than 48 hours, chemical preservation is necessary. Refer to the “Handling, Storage, and Preservation” section (Section 4) for more detailed preservation recommendations.
4. Ensure the temperature and pH of preservation water guidelines are followed during shutdowns.
5. Take care that the permeate back pressure never exceeds 4.5 psi (0.3 bar) when the system is shutdown. Ensure that check valves or relief valves are installed in the permeate line of individual trains.

2.6 System Operation Monitoring

Monitoring and collection of all relevant data during RO operation is necessary to ensure a reliable and high-quality performance. Additionally, well-logged records are fundamental for troubleshooting and handling of complaints. **Table 2** gives an overview of essential data to be logged during RO operation. **Table 3** gives an overview of typical water analysis parameters. Please note that both tables serve as guidelines for RO system operators. Data selection and its logging frequency, as well as specific selection of ions for analysis, should always be tailored to the specific application and its requirements.

Table 2: Overview of essential data to be logged during RO operation.

Parameters	Online monitoring	Daily	Periodically	Alarm & safety system
Date and time of data logging		X		
Total operating hours		X		
Number of vessels in operation		X		
Feed conductivity	X	X		
Feed pH	X	X		X
Feed temperature	X	X		X
Feed pressure	X	X		X
Feed free chlorine concentration	X	X		X
Feed antiscalant dosing		X		X
Feed fouling indicator (SDI_{15})			X	X
Feed turbidity (NTU)			X	X
Feed hardness			X	
Feed composition			X	
Concentrate conductivity	X	X		
Concentrate pH	X	X		
Concentrate flow rate	X	X		X
Concentrate pressure of each stage	X	X		
Total permeate conductivity	X	X		X
Total permeate flow rate	X	X		X
Permeate pressure		X		X
Permeate conductivity of each vessel			X	
Permeate individual ion concentration			X	
Pressure drop of each stage		X		X
Total recovery ratio		X		X
Recovery ratio of each stage			X	

Table 3: Overview of typical water analysis parameters.

Parameters		Essential	Optional
Conductivity		X	
pH		X	
Temperature		X	
Free chlorine		X	
Total dissolved solids	TDS	X	
Chemical oxygen demand	COD		X
Biological oxygen demand	BOD		X
Total organic carbon	TOC		X
Chloride	Cl^-		X
Nitrate	NO_3^-		X
Bicarbonate	HCO_3^-		X
Sulfate	SO_4^{2-}		X
Phosphate	PO_4^{3-}		X
Fluoride	F^-		X
Sodium	Na^+		X
Potassium	K^+		X
Ammonium	$NH4^+$		X
Calcium	Ca^{2+}		X
Magnesium	Mg^{2+}		X
Strontium	Sr^{2+}		X
Barium	Ba^{2+}		X
Iron as ion	Fe^{2+}		X
Manganese	Mn^{2+}		X
Silicate	SiO_2		X
Silicic acid	SiO_3^-		X
Carbon dioxide	CO_2		X
Hydrogen sulfide	H_2S		X

2.7 Data Normalization

The performance of an RO system will vary depending on feed water characteristics and operating conditions, such as TDS, temperature, pressure, or recovery ratio. To determine whether altered system performance is due to changed feed water or operating conditions, or whether it is caused by actual membrane performance decline as a result of e.g., membrane fouling, operating data must be taken at regular intervals and then normalized to baseline reference conditions. Normalization is strongly recommended for measured permeate flow rate and permeate TDS or salt passage, as it allows early detection of potential issues so corrective actions can be initiated. The reference condition may be the initial or designed performance of the RO system. Data normalization equations are given below.

2.7.1 Normalized Permeate Flow Rate

$$Q_N\ (\mathrm{GPD}) = Q_{op} \cdot \frac{NDP_{ref}}{NDP_{op}} \cdot \frac{TCF_{op}}{TCF_{ref}}$$

Q_N (GPD) = Permeate flow rate normalized
Q_{op} (GPD) = Permeate flow rate at operating condition
NDP_{ref} (psi) = Net driving pressure at reference condition
NDP_{op} (psi) = Net driving pressure at operating condition
TCF_{op} (–) = Temperature correction factor at operation condition
TCF_{ref} (–) = Temperature correction factor at reference condition

2.7.2 Net Driving Pressure

$$NDP\ (\mathrm{psi}) = P_F - \frac{\Delta P}{2} - P_P - \pi$$

NDP (psi) = Net driving pressure
P_F (psi = Feed pressure
ΔP (psi) = Differential pressure feed-concentrate
P_P (psi) = Permeate pressure
π (psi) = Osmotic pressure average

2.7.3 Temperature Correction Factor

$$TCF\ (–) = \exp\left[2903 \cdot \left(\frac{1}{273 + T} - \frac{1}{298}\right)\right]$$

TCF (–) = Temperature correction factor
T (°C) = Temperature in degrees celcius

Full details of the TCF for Aquaporin Inside® Industrial RO Membrane Elements may be found in the Appendix.

2.7.4 Osmotic Pressure Average

$$\pi\ (\mathrm{psi}) = \frac{(c_{FC} - c_P)}{795}$$

π (psi) = Osmotic pressure average
c_{FC} (ppm) = Feed - concentrate average concentration
c_P (ppm) = Permeate concentration

2.7.5 Feed - Concentrate Concentration Average

$$c_{FC}\ (\mathrm{ppm}) = c_F \cdot \frac{\ln \frac{1}{1 - Y}}{Y}$$

c_{FC} (ppm) = Feed - concentrate concentration average
c_F (ppm) = Feed concentration
Y (–) = Recovery ratio

2.7.6 Salt Passage

$$SP\ (–) = \frac{C_P}{C_{FC}}$$

SP (-) = Salt passage
c_P (ppm) = Permeate concentration
c_{FC} (ppm) = Feed-concentrate concentration average

2.7.7 Normalized Permeate TDS

$$c_{P_n}\ (\mathrm{ppm}) = c_{P_{op}} \cdot \frac{NDP_{op}}{NDP_{ref}} \cdot \frac{c_{FC\,ref}}{c_{FC\,op}}$$

c_{P_n} (ppm) = Permeate concentration normalized
$c_{P_{op}}$ (ppm) = Permeate concentration at operating condition
NDP_{ref} (psi) = Net driving pressure at reference condition
NDP_{op} (psi) = Net driving pressure at operating condition
$c_{FC_{ref}}$ (ppm) = Feed - concentrate concentration average at reference condition
$c_{FC_{op}}$ (ppm) = Feed - concentrate concentration average at operating condition

2.8 Precautions During System Operation

- FREE CHLORINE. Any oxidizing agent, such as free chlorine, must be eliminated from the feed water prior to coming into contact with the RO membrane. Even very low concentrations in the feed stream will result in irreversible damage to the RO membrane due to oxidation. Adequate pretreatment and monitoring of the feed water must be in place.
- PARTICULATE MATTER. Any particulate matter must be eliminated from the feed water prior to coming into contact with the RO membrane. Particulate matter can accumulate on the RO membrane surface and cause mechanical damages or block the RO element feed channel. Adequate pretreatment and monitoring of the feed water must be in place.
- LUBRICATION. Any lubricants that contain hydrocarbons, such as petroleum or vegetable oil-based lubricants, must be strictly avoided when lubricating adapter O-rings and brine seals. These lubricants will damage the RO membrane’s core tubes and interconnectors. Suitable lubricants include glycerin and silicon-based lubricants.
- HIGH TEMPERATURE AND PRESSURE. Operation outside of the temperature and pressure limits stated in the product datasheet must be avoided. These conditions can lead to the collapse of the RO membrane support, tightening of the RO membrane active layer, embossing of the RO membrane onto the permeate carrier, and/or mechanical damage to the RO element.

3

Cleaning

3.1 Introduction

The surface of an RO membrane is subject to fouling by suspended solids, colloids, precipitates, organics, and biological matter. Pre-treatment of feed water prior to the RO process is required to prevent fouling as much as possible. The nature and intensity of fouling depends on several factors, such as the quality of the feedwater, the system recovery rate, and operating conditions.

To ensure long membrane lifetime and optimal membrane performance, periodic membrane cleaning is required. Membrane clean-in-place (CIP) should be performed when the RO membranes show evidence of fouling, prior to a long-term shutdown, or as scheduled routine maintenance. Fouling of membrane elements is indicated by performance decline, i.e. decreasing permeate flowrate and/or higher solute passage. Another side effect of fouling is an increased pressure drop between the feed and concentrate side. To avoid permanent performance loss and membrane damage, membrane CIP should be performed at the latest when one or more of the following occur:

- Normalized permeate flow has decreased 10% since startup or last cleaning
- Normalized salt passage has increased 10% since startup or last cleaning
- Normalized pressure drop from feed to concentrate has increased 15% since startup or last cleaning.

Membrane CIP can be accomplished very effectively due to high pH stability and temperature tolerance of the Aquaporin Inside® Industrial RO Membrane Elements. The choice of membrane CIP protocol and CIP chemicals needs to be tailored to the specific fouling problem. Note that a wrong choice can make a situation worse. Therefore, the type of foulants on the membrane surface should be determined prior to cleaning, e.g. through analysis of performance data, analysis of feedwater characteristics and foulants, reference to previous cleanings, etc.

3.2 Recommended Membrane CIP Protocol

The RO membrane elements can be cleaned-in-place in the pressure vessels by soaking and circulating the cleaning solution across the high-pressure side of the membrane. RO cleaning procedures may vary depending on application and situation. The recommended standard membrane CIP consists of an alkaline cleaning followed by an acidic cleaning. Below CIP protocol should be followed for each cleaning solution.

1. Prior to introducing any cleaning solutions, it is recommended to flush the elements with clean water to displace any feed/brine solution. Flush water should be RO permeate or deionized water. Flushing flow rates should be half of the cleaning flow rates listed in **Table 4**.
2. Prepare the cleaning solution and adjust the temperature and pH to the target values. Temperature and pH limits are shown in **Table 5**. Recommended generic cleaning solutions are shown in **Table 6**.
3. Pump the cleaning solution into the pressure vessel at low feed flow rates and pressures. The flow rate should be half of the cleaning flow rates listed in **Table 4**. The pressure should be low enough that ideally no permeate is produced. Discard the concentrate, as necessary, to prevent dilution of the cleaning solution or readjust the pH and temperature to the targets.
4. After the clean water or process water has been displaced, circulate the cleaning solution at feed flow rates and pressures according to **Table 4**. If required, readjust the pH and temperature to the target values. pH and temperature of the cleaning solution should be monitored, controlled, and kept below the maximum allowable values during the whole cleaning cycle (**Table 5**). A standard cleaning consists of 30 minutes circulation.
5. After circulation, it is recommended to stop the pump and allow the membrane to soak in the cleaning solution. The soak time can vary from 30 minutes to 8 hours. A standard cleaning consists of 30 minutes soaking. An extended soak period is beneficial for difficult or excessive fouling. During long soak periods, circulate the cleaning solution slowly at ca. 1/10 of the flow rates stated in **Table 4** or in intervals to monitor and control the target temperature and pH.
6. After soaking, it is recommended to circulate for another 30 minutes. Temperature and pH should be monitored and controlled.
7. After the cleaning cycle, RO permeate or deionized water at minimum 20 °C is recommended for flushing out the cleaning solution and remaining foulants.
8. A second cleaning with a different cleaning solution can be started at this point, if required. Otherwise, flush membrane elements for at least 30 minutes with permeate directed to drain or until the permeate is clear and permeate pH has normalized.

Table 4: Cleaning feed flow rates during circulation.

Element Diameter	**Feed pressure**	**Feed flow rate per pressure vessel**	
[inches]	[bar]	[GPM]	[LPM]
4	1-4	9-12	34-45
8	1-4	36-48	136-182

Table 5: Temperature ranges and pH limits during cleaning.

Temperature Range	**> 45 °C**	**>35 - 45 °C**	**>25 - 35 °C**	**≤ 25 °C**
pH limit for CIP	Contact Aquaporin for assistance	pH 2.0 - 10.5	pH 1.0 – 11.0	pH 1.0 – 12.0

3.3 Cleaning Chemicals

Choosing the right cleaning chemicals is important since harsh and frequent membrane cleaning will shorten the membrane life, and sometimes a wrong choice of cleaning chemicals can worsen the fouling situation. The membrane cleaning will be more effective if it is tailored to the specific fouling problem. Therefore, the type of foulants should be determined prior to cleaning. **Table 6** lists the recommended simple cleaning chemicals depending on the type of foulants.

Generally, alkaline cleaners are used to remove organic fouling including biological matter, while acidic cleaners are used to remove inorganic precipitates including iron. If the elements suffer from inorganic precipitation and organic fouling, it is highly recommended to start with the alkaline cleaning. The acidic cleaning should only be performed once all organic, colloidal and biofouling has been removed, as acid cleaners can react with organic material and worsen the fouling problem. Sulfuric acid should not be used for cleaning because of the risk of calcium sulfate precipitation. RO permeate or deionized water should be used for the preparation of cleaning solutions.

Specialty cleaning chemicals are frequently used in the industry. Most of them are compatible with Aquaporin membranes in short term tests. For long term compatibility, please contact the cleaning chemical provider and Aquaporin for assistance. In any case, make sure that the given temperature and pH limits are not exceeded.

Table 6: Recommended cleaning solutions and alternatives.

Foulant	Cleaning solution	Alternative 1	Alternative 2
Carbonate scale	0.2 wt% HCl pH 1-2, max. 35 °C	2.0 wt% citric acid	0.5% wt% H_3PO_4 pH 1-2, max. 25 °C
Iron fouling	1.0 wt% $Na_2S_2O_4$ pH 5, max. 30 °C	2.0 wt% citric acid	0.5% wt% H_3PO_4 pH 1-2, max. 25 °C
Sulfate scale	0.1 wt% NaOH + 1.0 wt% Na_4EDTA pH 12, max. 25 °C	-	-
Biofouling	0.1 wt% NaOH pH 12, max. 25 °C	0.1 wt% NaOH + 1.0 wt% Na_4EDTA pH 12, max. 25 °C	-
Silica fouling	0.1 wt% NaOH pH 12, max. 25 °C	-	-
Organic fouling	Step 1: 0.1 wt% NaOH pH 12, max. 25 °C Step 2: 0.2 wt% HCl pH 2, max. 45 °C	Step 1: 0.1 wt% NaOH + 1.0 wt% Na_4EDTA pH 12, max. 25 °C Step 2: 0.2 wt% HCl pH 2, max. 45 °C	-

3.4 Safety Precautions During the Cleaning Procedure

When using cleaning chemicals, follow accepted safety practices. Consult the chemical manufacturer for detailed information about safety, handling, and disposal.

Respect the temperature and pH limits stated in **Table 5**. For cleanings that require conditions exceeding these limits, please contact Aquaporin for assistance.
Use the least harsh cleaning conditions possible. This includes the cleaning parameters of pH, temperature, and contact time. This will optimize the lifetime of the membrane.

Thoroughly rinse the first cleaning solution from the element before introducing the next solution.
After cleaning, the elements should be flushed with preferably permeate or deionized water and at reduced flow and pressure to flush the bulk of the cleaning solution from the elements before resuming to normal operating pressures and flows. Further, the permeate must be directed to drain for at least 30 minutes or until the water is clear as cleaning chemicals will be present on the permeate side.

Cleaning and flushing flows should usually be in the same direction as the normal feed flow to avoid potential element telescoping and element damage.

4

Handling, Storage, and Preservation

4.1 Introduction

Aquaporin Inside® Industrial RO Membrane Elements should be handled in such a way that biological growth and change in membrane performance during storage, shipping or system shutdowns are prevented. The elements should preferably be stored and shipped outside the pressure vessels and loaded into the pressure vessels just prior to start-up. Element preservation is needed for long-term storage of new and used elements, and system shutdown of > 48 hours.

4.2 Handling and Storage of New Membrane Elements

New membrane elements are shipped either in dry condition or as wet and preserved membrane elements. Wet membrane elements are preserved in a standard storage solution containing a buffered 1 wt% food-grade sodium metabisulfite (SMBS). The storage solution prevents biological growth during storage and shipping of membrane elements. It is advised to flush membrane elements prior to use to eliminate residual preservative in the product stream. To maintain good membrane element performance, store and handle the membrane elements with the following guidelines:

1. Store the membrane elements in a cool, dry place within a temperature range of 5 °C to 35 °C (41 °F to 95 °F). Avoid storage in direct sunlight.
2. During transportation, the membrane elements should not be exposed to temperatures below freezing (0 °C or 32 °F), or above 40 °C (104 °F). If the duration of transport is longer than 2 months, the temperature should not exceed 35 °C (95 °F).
3. If the ambient temperature in the membrane element storage area is expected to drop below freezing point (0 °C or 32 °F), measures should be taken to keep the membrane elements at a temperature above freezing. Do not allow membrane elements to freeze.
4. Do not stack more than 5 layers of carton boxes when re-stacking from originally delivered packing (export packing).
5. Always keep the original membrane element packaging dry to preserve their structural integrity.
6. To avoid damage, handle each membrane element with care. Avoid dropping the membrane element. To minimize the potential for contamination, handle the membrane elements with clean hands or gloves. Take precautions to keep the exterior of membrane element clean.
7. Wet membrane elements are shipped in sealed oxygen impermeable plastic bags and sturdy carton boxes. Only open the membrane element boxes directly prior to membrane element installation.
8. Store and ship membrane elements as packaged by Aquaporin and only load membrane elements into pressure vessels directly before start-up.

Caution: Avoid direct skin and eye contact with the storage solution and fiberglass wrapping of the membrane elements. Use safety rubber gloves and safety glasses during handling.

4.3 Storage of Used Membrane Elements

Any membrane element that has been used and removed from the pressure vessel for storage or shipping must be preserved in a preservation solution as follows:

1. Using softened, good-quality water (preferably RO permeate), prepare the preservation solution of 1 wt% food-grade SMBS.
2. Soak the membrane elements for about 1 hour in the storage solution, keeping them standing in a vertical position so that the entrapped air can escape. Allow excess preservative to drip out, and then seal the membrane element into an oxygen barrier plastic bag. Seal and label the bag(s), indicating packaging date & details of the storage solution. We recommend reusing the original bag or original spare bags available from us. Do not fill the plastic bag with the preservation solution – the moisture in the element is sufficient, and leaking bags might create a problem during transport.
3. Storage conditions for used and repackaged membrane elements are the same as for new membrane elements explained earlier in the "Handling and Storage of New Membrane Elements" section.
4. Preserved membrane elements should be visually inspected for biological growth every three months. When the preservation solution appears to be not clear, or after six months, the membrane element should be removed from the bag, soaked in a fresh preservation solution, and repacked.
5. The pH of the preservation solution must never drop below pH 3. A pH decrease can occur when bisulfite is oxidized to sulfuric acid. Therefore, the pH of the bisulfite preservation solution should be spot checked at least every 3 months. Re-preservation is mandatory when the pH is 3 or lower.
6. Wear protective gloves and sleeves to avoid prolonged contact with skin and sleeves when working with preservative solution.

4.4 Short-term RO System Shutdowns

Short-term shutdown refers to the period when an RO plant remains out of operation for less than 48 hours with membrane elements in place. Procedure for the storage of membrane elements during short term shutdown is as follows:

1. Flush the membrane elements with pre-treated RO feed water at low pressure (0.1 - 0.2 MPa) for 10 - 20 min. The vent valve should be kept open to ensure the venting of any gases which may be present in the system.
2. After flushing, the pressure tube is filled with pre-treated RO feed water.
3. Close the vent valve.

4.5 Long-term RO System Shutdowns

Long-term shutdown refers to the period when an RO plant remains out of operation for more than 48 hours with membrane elements in place. Depending on the previous operational history of the plant, it will be necessary in almost all cases to clean the membrane elements in place (CIP) prior to shutdown and preservation. This applies to cases when the membrane elements are known or assumed to be fouled. Prepare each RO train as follows:

1. Clean the membrane elements in place (CIP). Please refer to the "Cleaning section (Section 3) for full details.
2. Completely immerse the membrane elements in the pressure vessels in a solution of 1.0 - 1.5% food-grade SMBS, venting the air outside of the pressure vessels. Use the overflow technique: circulate the SMBS solution in such a way that the remaining air in the system is minimized after the recirculation is completed. After the pressure vessel is filled, the SMBS solution should be allowed to overflow through an opening located higher than the upper end of the highest-pressure vessel being filled.
3. When the RO section is filled with SMBS solution, close the valves to retain the SMBS solution in the RO section. Any contact with oxygen will oxidize the SMBS and void the preservative properties.
4. Repeat steps 2 and 3 with fresh preservation solution every 30 days if the temperature is below 27 °C (80 °F). If the temperature is above 27 °C (80 °F), check the pH once a week. When the pH value drops to 3 or lower, change the preservation solution.

5. During the shutdown period, the plant must be kept frost-free, and the temperature must not exceed 45 °C (113 °F).
6. When the RO system is ready to be returned to service, flush the system for approximately one hour using low-pressure feed water with the permeate dump valve open to drain; then flush it at high pressure for 5 to 10 minutes with the permeate dump valve open to drain. Before returning the RO system to service, check for any residual SMBS in the permeate, e.g. by electrical conductivity or TDS measurement. Electrical conductivity or TDS should be at normal levels.

4.6 Disposal of Used Membrane Elements

Used membrane elements can be disposed of as municipal waste, provided that:

1. No preservation solution or other hazardous liquid is contained in the membrane element, and
2. No hazardous substances, such as heavy metals, organic pollutants, radioactive material, etc., have been deposited on the membrane surface and inside the membrane elements during operation. Be aware when membrane elements have been used for wastewater treatment or contaminant removal.

5

Troubleshooting

5.1 Introduction

This guide contains useful techniques when troubleshooting reverse osmosis (RO) systems. The objective of troubleshooting on RO systems is to identify membrane system irregularities and to investigate modes of membrane system failures, with the intent of eventually restoring membrane performance.

Despite pretreatment and attention to system hydraulics, most RO systems will eventually show degradation in performance due to membrane ageing and fouling. This performance degradation manifests itself as a slow and continuous loss in permeate flow, increase of salt passage, or increase in pressure drop.

If one of these three parameters, or a combination of them, deviates slowly from the normalized value, it may indicate normal fouling and scaling, which can possibly be removed by proper membrane cleaning. However, a fast and/or sudden performance decline indicates faulty system operation and/or operation outside the original system design criteria (e.g., a change in feed water quality, change of pretreatment chemicals, etc.). In these cases, it is essential that the proper corrective measures are taken as soon as possible, as any delay decreases the chance of restoring system performance and may lead to other problems.

A prerequisite for early detection of potential problems is consistent record keeping and performance normalization, including proper calibration of all instruments. Without accurate readings, it may not be possible to detect a problem early and identify the root cause.

After the problem has been detected, the next step is to localize the problem and to identify the causes. This can be done using the data in the record keeping log sheet or additional online measurements. If the data are not sufficient to determine the causes, one or more membrane elements must be taken out of the system and analyzed using either nondestructive or destructive methods.

5.2 System Evaluation

5.2.1 Instrument Calibration

Instrument calibration is the first thing to check during troubleshooting as wrong instrumentation can lead to a false alarm or cause a real increase in salt passage to be missed.

Online TDS meters should be verified by measuring feed and permeate TDS manually with a calibrated TDS meter. If the values do not align, recalibrate the online meter according to the manufacturers' instructions. The probe should also be inspected to ensure proper mounting and make sure that accumulated residual material is not interfering with the reading.

Mechanical pressure gauges should be verified using a calibrated pressure gauge. This can be mounted with a quick-connect fitting. Electronic pressure sensors have the potential for greater accuracy. However, they are subject to sensor drift and damage resulting from vibration of the high-pressure pumps. To reduce the effects of vibration, the sensor can be mounted remotely and connected to the high-pressure piping with a length of stainless steel or high-pressure nylon tubing.

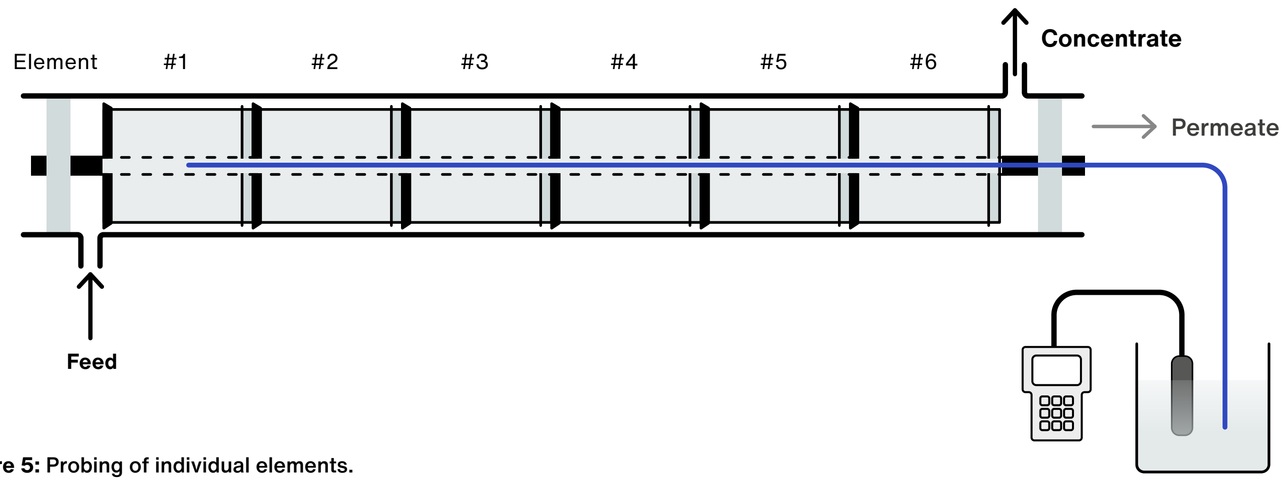

Figure 5: Probing of individual elements.

The pH meters should be verified and, if necessary, calibrated using buffer solutions with a known pH. The temperature readings should be verified with an accurate thermometer.

5.2.2 Visual Inspection

After instrument validation and calibration, a visual inspection of the system is a helpful troubleshooting tool.

The general cleanliness of the RO system should be investigated. Mold and biological growth in tanks and pipes are indicators of biofouling. A wet and slippery surface on the feed side of a pressure vessel indicates biofilm growth. The concentrate side of pressure vessels may show signs of scaling. Torn, damaged, or misplaced O-rings should be replaced immediately.

The efficiency of cleaning agents may indicate the presence of fouling (i.e. if a cleaning solution contains high amounts of foulant when it exits the RO system, fouling is most likely present inside the system). To establish the type of foulant present, analyze and compare samples of the cleaning solution before and after cleaning-in-place (CIP). Please refer to the "Cleaning" section (Section 3) for full details.

5.2.3 Localizing High Salt Passage

If an RO system exhibits high salt passage, it is important to localize the source. A drop in salt rejection may be uniform throughout the system, or it could be limited to the front or tail end of the system. It could be a general plant failure, or it could be limited to one or a few individual vessels or elements.

To localize high salt passage, the RO system should be profiled. This requires that the TDS, conductivity, and other relevant quality values are checked on all individual vessels. In a well-designed system, there will be a sample port located in the permeate stream from each vessel where samples can be taken. Care must be taken during sampling to avoid mixing the permeate sample with permeate from other vessels. All permeate samples should be tested with a TDS or conductivity meter to ascertain their concentration of dissolved solids. The permeate samples from all pressure vessels in the same stage should give readings in the same range. Additionally, the feed concentration to each stage must be measured. The resulting salt passage values can then be assigned to the stages and individual vessels, respectively.

If one pressure vessel shows a significantly higher permeate TDS than the other vessels in the same stage, then this vessel should be probed (see **Figure 5**). Probing involves the insertion of a plastic tube (approx. 1/4" for an 8" module) into the full length of the permeate tube. The probe will then divert water from the permeate stream of that vessel when the RO system operates at normal operating conditions. A few minutes should be allowed to rinse out the tubing and allow the RO system to equilibrate. The TDS of the permeate sample from the tubing can then be measured manually. This measurement should reflect the TDS of the permeate being produced by the RO element at that location.

5.2.4 Membrane Element Evaluation

If the causes of plant performance loss are unknown, or they have to be confirmed, one or more elements in the system should be analyzed individually. The element(s) that should be analyzed are those with an increase in their conductivity profile.

When there is a general plant failure, a front-end element or a tail-end element should be selected, depending on where the problem is located. Typical front-end problems are due to fouling; typical tail-end problems come from scaling. Vessels/elements with these problems usually show low permeate flow rate and sometimes a high salt passage from severe fouling and/or scaling.

When the problem cannot be localized, an element from both ends of the system should be taken.

If high salt passage is found only in one or a few elements in one or a few pressure vessels, then it is most likely that the element(s) have mechanical damages, such as punctures on the membrane surface, glue line failure, a cracked membrane centerfold, or damaged O-rings, including brine seals.

Damaged O-rings and brine seals can be verified easily by visually inspecting the failed elements. Damaged membranes and glue line failures can only be visually verified following an autopsy of the elements. Alternatively, physical damages can be verified by running a dye test alongside a salt rejection/flux test by using a small test line containing methylene blue or rhodamine B. If the dye is detected visually or spectroscopically in the permeate, it indicates that there is considerable damage in the membrane or glue line. The element can then be autopsied to assess the cause of the damage.
If membrane damage has been caused by chemicals, such as chlorine or concentrated acid, a high salt passage along with a higher than normal permeate flow rate would occur, usually in all the elements of the first array. If the high dosage of chemicals in the system is not corrected immediately, the membranes in the second array will also be damaged.

5.2.5 Indicators, Causes, and Corrective Measures for Performance Loss

The possible causes of RO system performance decline can be diagnosed through system performance indicators. Normalized permeate flow rate, normalized salt passage, and pressure drop are the three main indicators for identifying the cause of lost membrane performance.

The troubleshooting matrix in **Table 7** shows trends in normalized performance data, their causes and corrective measures, as well as the locations where they commonly occur.

Table 7: RO system troubleshooting guide.

Permeate flow	Salt passage	Pressure drop	Cause	Corrective measure	Usual location
Up	Up*	Stable	Oxidation damage	Replace element Improve pretreatment	1st stage
Up	Up*	Stable	Membrane leak	Replace element	Random
Up	Up*	Stable	O-ring leak	Replace O-ring	Random
Up	Up*	Stable	Leaking product tube	Replace element	Random
Down*	Up	Up	Scaling	Cleaning Scaling control	Last stage
Down*	Up	Up	Colloidal fouling	Cleaning Improve pretreatment	1st stage
Down	Stable	Up*	Biofouling	Cleaning Improve pretreatment	All stages
Down*	Stable	Stable	Organic fouling	Cleaning Improve pretreatment	All stages
Down*	Down	Stable	Compaction	Replace element	All stages

*Main symptom

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7

Appendix

Shown below are the full details for the Temperature Correction Factors (TCF) for Aquaporin Inside® Industrial RO Membrane Elements.

Table 8: TCF for Aquaporin Inside® Industrial RO Membrane Elements

T (°C)	TCF	T (°C)	TCF	T (°C)	TCF	T (°C)	TCF	T (°C)	TCF	T (°C)	TCF	T (°C)	TCF	T (°C)	TCF	T (°C)	TCF
5.0	2.070	9.0	1.755	13.0	1.514	17.0	1.276	21.0	1.140	25.0	1.000	29.0	0.900	33.0	0.809	37.0	0.696
5.1	2.059	9.1	1.749	13.1	1.505	17.1	1.271	21.1	1.136	25.1	0.998	29.1	0.898	33.1	0.806	37.1	0.692
5.2	2.051	9.2	1.741	13.2	1.500	17.2	1.266	21.2	1.133	25.2	0.994	29.2	0.895	33.2	0.804	37.2	0.690
5.3	2.044	9.3	1.734	13.3	1.495	17.3	1.263	21.3	1.131	25.3	0.991	29.3	0.893	33.3	0.801	37.3	0.688
5.4	2.035	9.4	1.727	13.4	1.486	17.4	1.261	21.4	1.129	25.4	0.988	29.4	0.891	33.4	0.798	37.4	0.686
5.5	2.028	9.5	1.720	13.5	1.483	17.5	1.259	21.5	1.126	25.5	0.986	29.5	0.888	33.5	0.795	37.5	0.681
5.6	2.020	9.6	1.714	13.6	1.477	17.6	1.255	21.6	1.123	25.6	0.983	29.6	0.886	33.6	0.793	37.6	0.678
5.7	2.011	9.7	1.707	13.7	1.469	17.7	1.250	21.7	1.120	25.7	0.981	29.7	0.883	33.7	0.790	37.7	0.676
5.8	2.003	9.8	1.700	13.8	1.460	17.8	1.246	21.8	1.115	25.8	0.979	29.8	0.880	33.8	0.787	37.8	0.674
5.9	1.996	9.9	1.693	13.9	1.454	17.9	1.241	21.9	1.111	25.9	0.976	29.9	0.878	33.9	0.785	37.9	0.670
6.0	1.989	10.0	1.686	14.0	1.448	18.0	1.237	22.0	1.109	26.0	0.974	30.0	0.875	34.0	0.782	38.0	0.677
6.1	1.980	10.1	1.678	14.1	1.440	18.1	1.235	22.1	1.104	26.1	0.971	30.1	0.873	34.1	0.780	38.1	0.675
6.2	1.974	10.2	1.671	14.2	1.435	18.2	1.232	22.2	1.100	26.2	0.968	30.2	0.871	34.2	0.777	38.2	0.671
6.3	1.966	10.3	1.666	14.3	1.430	18.3	1.228	22.3	1.095	26.3	0.966	30.3	0.869	34.3	0.775	38.3	0.667
6.4	1.955	10.4	1.662	14.4	1.422	18.4	1.225	22.4	1.091	26.4	0.962	30.4	0.867	34.4	0.772	38.4	0.663
6.5	1.949	10.5	1.658	14.5	1.416	18.5	1.223	22.5	1.089	26.5	0.961	30.5	0.865	34.5	0.770	38.5	0.660
6.6	1.942	10.6	1.650	14.6	1.411	18.6	1.220	22.6	1.086	26.6	0.958	30.6	0.863	34.6	0.767	38.6	0.658
6.7	1.935	10.7	1.644	14.7	1.406	18.7	1.215	22.7	1.082	26.7	0.955	30.7	0.860	34.7	0.765	38.7	0.655
6.8	1.927	10.8	1.639	14.8	1.402	18.8	1.213	22.8	1.078	26.8	0.953	30.8	0.859	34.8	0.762	38.8	0.653
6.9	1.919	10.9	1.709	14.9	1.396	18.9	1.211	22.9	1.074	26.9	0.951	30.9	0.856	34.9	0.758	38.9	0.650
7.0	1.910	11.0	1.633	15.0	1.392	19.0	1.207	23.0	1.071	27.0	0.948	31.0	0.854	35.0	0.756	39.0	0.648
7.1	1.902	11.1	1.625	15.1	1.388	19.1	1.202	23.1	1.069	27.1	0.945	31.1	0.851	35.1	0.754	39.1	0.646
7.2	1.896	11.2	1.619	15.2	1.381	19.2	1.200	23.2	1.066	27.2	0.943	31.2	0.849	35.2	0.751	39.2	0.643
7.3	1.889	11.3	1.612	15.3	1.375	19.3	1.195	23.3	1.062	27.3	0.941	31.3	0.846	35.3	0.749	39.3	0.641
7.4	1.878	11.4	1.605	15.4	1.371	19.4	1.191	23.4	1.059	27.4	0.939	31.4	0.844	35.4	0.744	39.4	0.637
7.5	1.869	11.5	1.599	15.5	1.366	19.5	1.189	23.5	1.054	27.5	0.936	31.5	0.842	35.5	0.742	39.5	0.635
7.6	1.862	11.6	1.593	15.6	1.359	19.6	1.186	23.6	1.051	27.6	0.934	31.6	0.840	35.6	0.740	39.6	0.631
7.7	1.855	11.7	1.589	15.7	1.351	19.7	1.184	23.7	1.047	27.7	0.931	31.7	0.838	35.7	0.737	39.7	0.628
7.8	1.849	11.8	1.583	15.8	1.345	19.8	1.180	23.8	1.044	27.8	0.928	31.8	0.836	35.8	0.733	39.8	0.625
7.9	1.841	11.9	1.578	15.9	1.338	19.9	1.175	23.9	1.040	27.9	0.926	31.9	0.834	35.9	0.730	39.9	0.622
8.0	1.835	12.0	1.574	16.0	1.332	20.0	1.173	24.0	1.036	28.0	0.924	32.0	0.832	36.0	0.728	40.0	0.618
8.1	1.827	12.1	1.566	16.1	1.328	20.1	1.171	24.1	1.033	28.1	0.921	32.1	0.829	36.1	0.725	40.1	0.616
8.2	1.819	12.2	1.559	16.2	1.320	20.2	1.168	24.2	1.029	28.2	0.918	32.2	0.827	36.2	0.722	40.2	0.613
8.3	1.813	12.3	1.553	16.3	1.314	20.3	1.163	24.3	1.025	28.3	0.915	32.3	0.824	36.3	0.718	40.3	0.609
8.4	1.806	12.4	1.548	16.4	1.308	20.4	1.160	24.4	1.022	28.4	0.913	32.4	0.822	36.4	0.714	40.4	0.605
8.5	1.800	12.5	1.543	16.5	1.302	20.5	1.157	24.5	1.018	28.5	0.910	32.5	0.820	36.5	0.712	40.5	0.601
8.6	1.794	12.6	1.539	16.6	1.297	20.6	1.153	24.6	1.015	28.6	0.908	32.6	0.817	36.6	0.710	40.6	0.599
8.7	1.788	12.7	1.531	16.7	1.291	20.7	1.151	24.7	1.011	28.7	0.907	32.7	0.815	36.7	0.706	40.7	0.596
8.8	1.769	12.8	1.525	16.8	1.386	20.8	1.147	24.8	1.007	28.8	0.904	32.8	0.813	36.8	0.704	40.8	0.592
8.9	1.761	12.9	1.520	16.9	1.281	20.9	1.143	24.9	1.003	28.9	0.902	32.9	0.811	36.9	0.700	40.9	0.587

Corrected Flowrate = Measured Flowrate · $TCF_{\text{Feedwater Temperature}}$

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