Operation Guide for Industrial Aquaporin Inside® RO Membrane Elements

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.

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.

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.

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.

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.

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.

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.

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 “Membrane Clean-in-Place (CIP) Guide for Industrial Aquaporin Inside® RO Membrane Elements”.

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.

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 (m³/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 (m³/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 (m³/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)

Element Loading

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.

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 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.

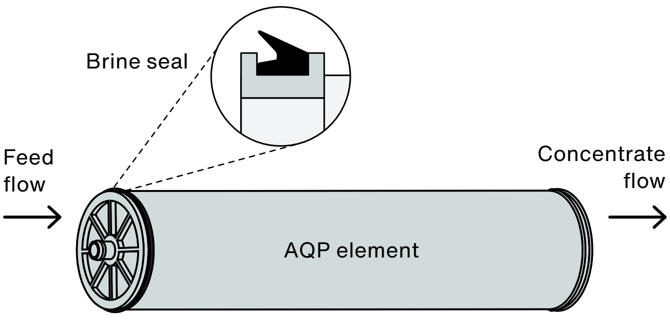

Figure 1: Orientation of brine seal.

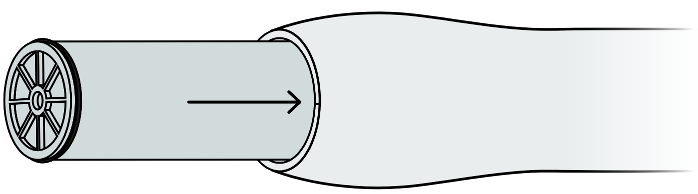

Figure 2: Insertion of first RO element.

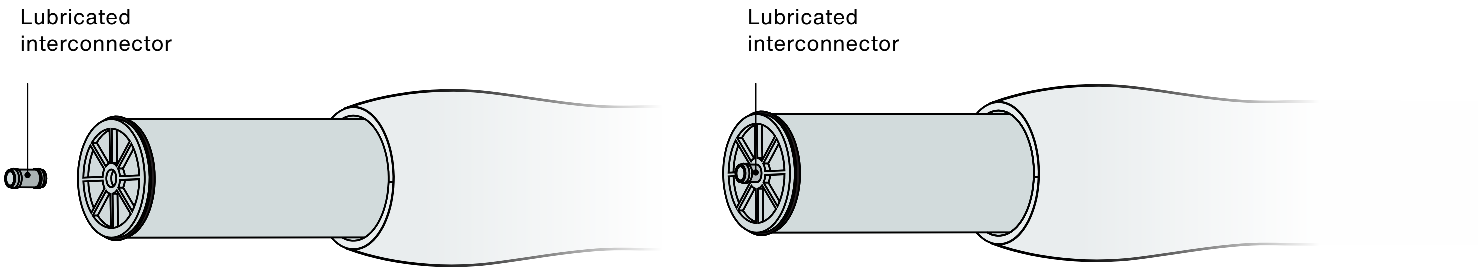

Figure 3: Installation of lubricated interconnector.

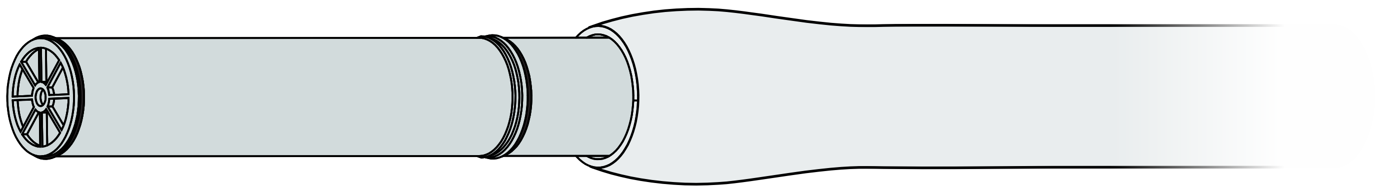

Figure 4: Insertion of next RO element.

System Start-up and Shutdown

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.

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.

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 of Industrial Aquaporin Inside® RO Membrane Elements" manual 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.

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

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.

Normalized Permeate Flow Rate

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

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_{ref} (–) = Temperature correction factor at reference condition
TCF_{op} (–) = Temperature correction factor at operation condition

Net Driving Pressure

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

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

Temperature Correction Factor

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

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

Osmotic Pressure Average

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

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

Feed - Concentrate Concentration Average

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

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

Salt Passage

$$SP\,(-) = \frac{C_P}{C_{FC}}$$

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

Normalized Permeate TDS

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

c_{P_n} (ppm) = Permeate concentration normalized
$c_{P_{ref}}$ (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

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.

Aquaporin A/S
Nymøllevej 78
2800 Kongens Lyngby
Denmark

Phone: +45 8230 3082
sales@aquaporin.com
aquaporin.com