FILMTEC
MEMBRANE ELEMENTS

Table of Contents

2.0 Introduction to Reverse Osmosis

3.0 Water Chemistry and Pretreatment

4.0 System Design

5.0 Assembly and Loading of Pressure Vessels

6.0 System Operation

7.0 Cleaning and Disinfection

8.0 Handling and Preservation

9.0 Troubleshooting

10.0 Addendum

1.0 Key Word Index

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2. Introduction to Reverse Osmosis

2.1 General Information

Since their development as practical unit operations in the late 1950's and early 1960's, reverse osmosis (RO) and ultrafiltration (UF) have been continually expanding the scope of their applications. Initially, reverse osmosis was applied to the desalination of sea water and brackish water. Increased demands on the industry to conserve water, reduce energy consumption, control pollution and reclaim useful materials from waste streams have made new applications economically attractive. In addition, advances in the fields of biotechnology and pharmaceuticals, coupled with advances in membrane development, are making membranes an important separation step, which, compared to distillation, offers energy savings and does not lead to thermal degradation of the products.

Basic membrane research with respect to the foundation of FilmTec Corporation and the development of the FILMTEC® FT30 membrane started in 1963 at the North Star Research Institute in Minneapolis, MN, USA.

Since then, products and product improvements have been developed in the North Star Laboratories, such as

- original thin film composite membrane
- microporous polysulfone
- first non-cellulose thin film composite membrane (NS-100)
- thin film composite membranes NS-200 and NS-300
- ultrathin cellulose hemodialysis membrane

An important development in the thin film composite approach was the discovery of microporous polysulfone support films in 1967 by John Cadotte. Not only did this result in twice the flux for ultrathin cellulose acetate composite membranes, but it subsequently led to the invention of four important non-cellulosic thin film composite membranes by Cadotte: NS-100, NS-200, NS-300 and finally the FT30. Each of these discoveries is either embodied in a commercial reverse osmosis membrane, or has led to a modified, closely-related commercial membrane. Microporous polysulfone itself has achieved widespread use as an ultrafiltration membrane.

In 1977 the FilmTec Corporation was founded in Minneapolis USA.

After important and dramatically evolving product changes and company development between 1981 and 1984, the FilmTec Corporation became a wholly owned subsidiary of The Dow Chemical Company in August 1985.

To assure supply of FILMTEC products to the rapidly growing reverse osmosis market, Dow has committed capital to expand its manufacturing capabilities and besides the production site in Minneapolis, established a second production site in Europe through the acquisition of the Membrane division of DDS (De Danske Sukkerfabriken) in December 1989.

Through the combination of selling only to approved water treatment companies and Dow's sales network sustained by Technical Service Centers, Dow assures the technical success of its FILMTEC products and the commercial and technical success of its customers.

For technical and commercial information on FILMTEC products, please contact one of the following Liquid Separations Sales offices.

Dow Suomi OY
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Dow France S.A.
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Dow Deutschland Inc.
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2.2 Desalination Technologies and Filtration Processes

Out of the several desalination processes considered, reverse osmosis, ion exchange, distillation and electrodialysis are the major processes used in desalination. Of lesser significance due to their practical application as well as their less beneficial operation, are refrigerant freezing, vacuum freezing, vapor compression and piezodialysis.

Reverse osmosis is in general the most economical process for desalination of brackish water and sea water. As a widely accepted technology, reverse osmosis became more and more competitive and is superior to the traditional thermal process when a comparison is made of capital investment and energy consumption.

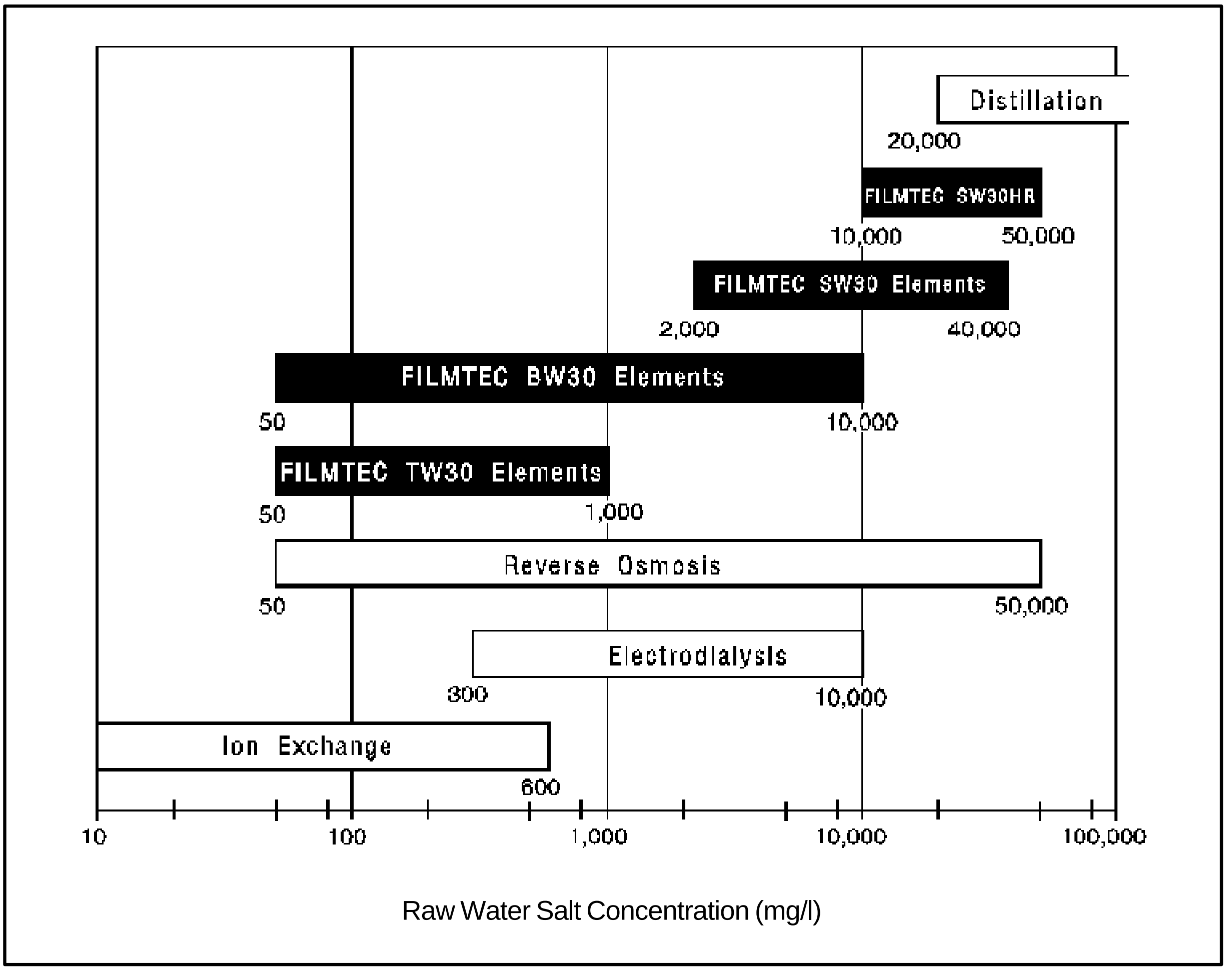


Figure 1: Major Desalination Processes

The most typical operating span of these four major desalination processes is shown in Figure 1, indicating also the standard operating ranges of the different FILMTEC® element types.
The various filtration technologies which currently exist can be categorized on the basis of the size of particles removed from a feed stream. Conventional macrofiltration of suspended solids is accomplished by passing a feed solution through the filter media in a perpendicular direction. The entire solution passes through the media, creating only one exit stream. Examples of such filtration devices include cartridge filters, bag filters, sand filters, and multimedia filters. Macrofiltration separation capabilities are generally limited to undissolved particles greater than 1 micron.

For the removal of small particles and dissolved salts, membrane separation systems are utilized which use a different method than conventional particle filtration. Termed crossflow membrane filtration (see Figure 2), this method uses a pressurized feed stream which flows parallel to the membrane surface. A portion of this stream passes through the membrane, leaving behind the rejected particles in the concentrated remainder of the stream. Since there is a continuous flow across the membrane surface, the rejected particles do not accumulate but instead are swept away by the concentrate stream. Thus, one feed stream is separated into two exit streams: the solution passing through the membrane surface (permeate) and the remaining concentrate stream.

There are four general categories of crossflow membrane filtration: Microfiltration, Ultrafiltration, Nanofiltration, and Reverse Osmosis.

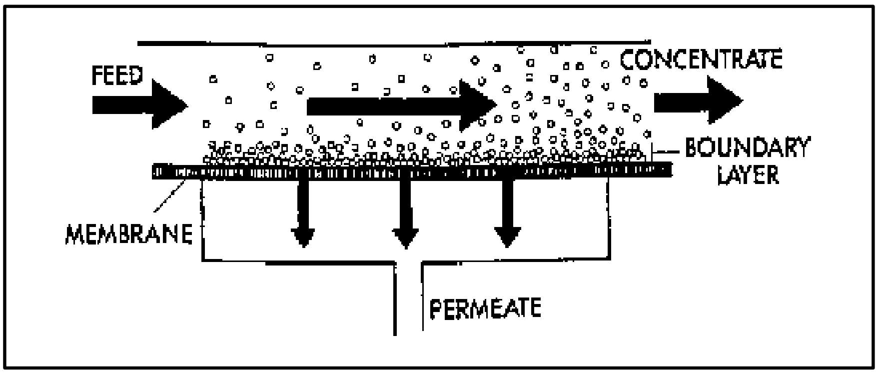


Figure 2: Crossflow Membrane Filtration

Microfiltration (MF)
Microfiltration removes particles in the range of approximately 0.1 to 1 micron. In general, suspended particles and large colloids are rejected while macromolecules and dissolved solids pass through the MF membrane. Applications include removal of bacteria, flocculated materials, or TSS (total suspended solids). Transmembrane pressures are typically 0.7 bar (10 PSI).

Ultrafiltration (UF)
Ultrafiltration provides macromolecular separation for particles in the 20 to 1,000 Angstrom range (up to 0.1 micron). All dissolved salts and smaller molecules pass through the membrane. Items rejected by the membrane include colloids, proteins, microbiological contaminants, and large organic molecules. Most UF membranes have molecular weight cut-off values between 1,000 and 100,000. Transmembrane pressures are typically 1 to 7 bar (15 to 100 PSI).

Nanofiltration (NF)
Nanofiltration refers to a speciality membrane process which rejects particles in the approximate size range of 1 nanometer (10 Angstroms), hence the term “Nanofiltration.” NF operates in the realm between UF and reverse osmosis. Organic molecules with molecular weights greater than 200-400 are rejected. Also, dissolved salts are rejected in the range of 20-98%. Salts which have monovalent anions (e.g. sodium chloride or calcium chloride) have rejections of 20-80%, whereas salts with divalent anions (e.g. magnesium sulfate) have higher rejections of 90-98%. Typical applications include removal of color and total organic carbon (TOC) from surface water, removal of hardness or radium from well water, overall reduction of total dissolved solids (TDS), and the separation of organic from inorganic matter in specialty food and wastewater applications. Transmembrane pressures are typically 3.5 to 16 bar (50 to 225 PSI).

Reverse Osmosis (RO)
Reverse osmosis is the finest level of filtration available. The RO membrane acts as a barrier to all dissolved salts and inorganic molecules, as well as organic molecules with a molecular weight greater than approximately 100. Water molecules, on the other hand, pass freely through the membrane creating a purified product stream. Rejection of dissolved salts is typically 95 to greater than 99%.

The applications for RO are numerous and varied, and include desalination of sea water or brackish water for drinking purposes, wastewater recovery, food and beverage processing, biomedical separations, purification of home drinking water and industrial process water. Also, RO is often used in the production of ultrapure water for use in the semiconductor industry, power industry (boiler feed water), and medical/laboratory applications. Utilizing RO prior to Ion Exchange (IX) dramatically reduces operating costs and regeneration frequency of the IX system. Transmembrane pressures for RO typically range from 14 bar (200 PSI) for brackish water to 69 bar (1,000 PSI) for sea water.

The normal range of filtration processes is shown in Figure 3:

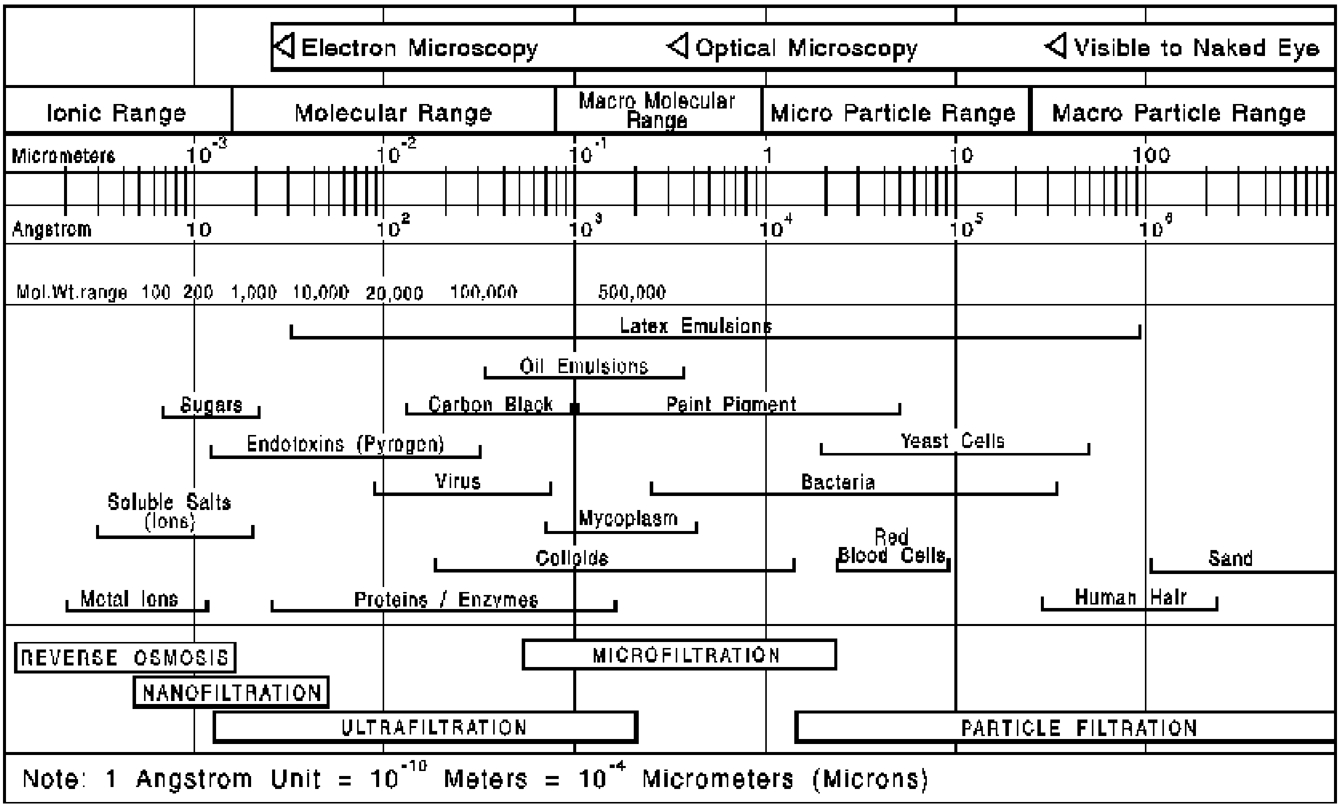


Figure 3: Ranges of Filtration Processes

2.3 Principle of Reverse Osmosis

2.3.1 How Reverse Osmosis Works

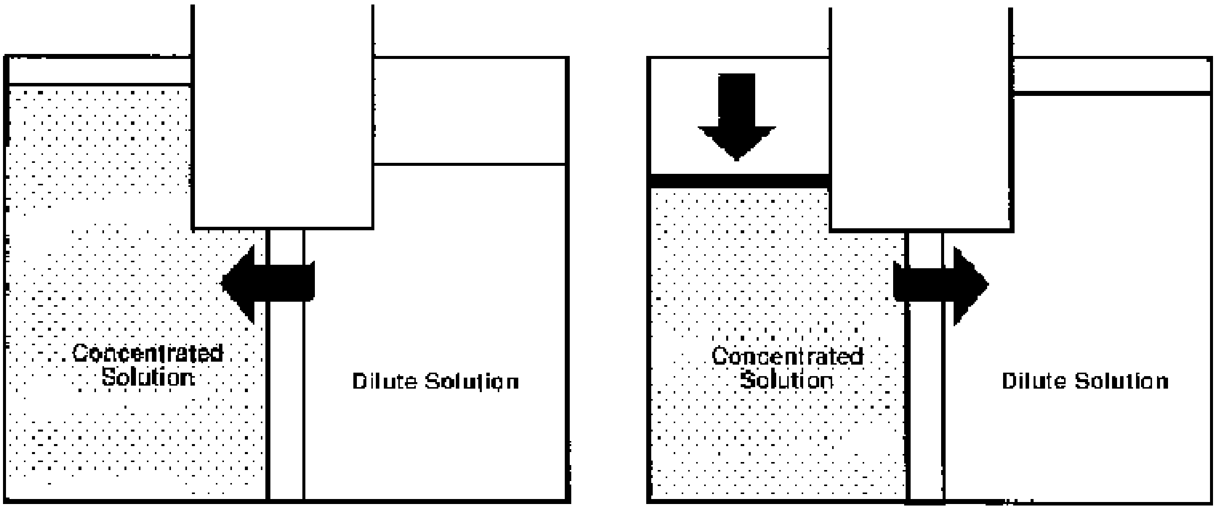
The phenomenon of osmosis occurs when pure water flows from a dilute saline solution through a membrane into a higher concentrated saline solution.

The phenomenon of osmosis is illustrated in Figure 1. A semi-permeable membrane is placed between two compartments. “Semi-permeable” means that the membrane is permeable to some species, and not permeable to others. Assume that this membrane is permeable to water, but not to salt. Then, place a salt solution in one compartment and pure water in the other compartment. The membrane will allow water to permeate through it to either side. But salt cannot pass through the membrane.

As a fundamental rule of nature, this system will try to reach equilibrium. That is, it will try to reach the same concentration on both sides of the membrane. The only possible way to reach equilibrium is for water to pass from the pure water compar-tment to the salt-containing compartment, to dilute the salt solution.

Figure 1 also shows that osmosis can cause a rise in the height of the salt solution. This height will increase until the pressure of the column of water (salt solution) is so high that the force of this water column stops the water flow. The equilibrium point of this water column height in terms of water pressure against the membrane is called osmotic pressure.

If a force is applied to this column of water, the direction of water flow through the membrane can be reversed. This is the basis of the term reverse osmosis. Note that this reversed flow produces a pure water from the salt solution, since the membrane is not permeable to salt.



Osmosis

Water diffuses through a semi-permeable membrane toward region of higher concentration to equalize solution strength. Ultimate height difference between columns is “osmotic” pressure.

Reverse Osmosis

Applied pressure in excess of osmotic pressure reverses water flow direction. Hence the term “reverse osmosis.”

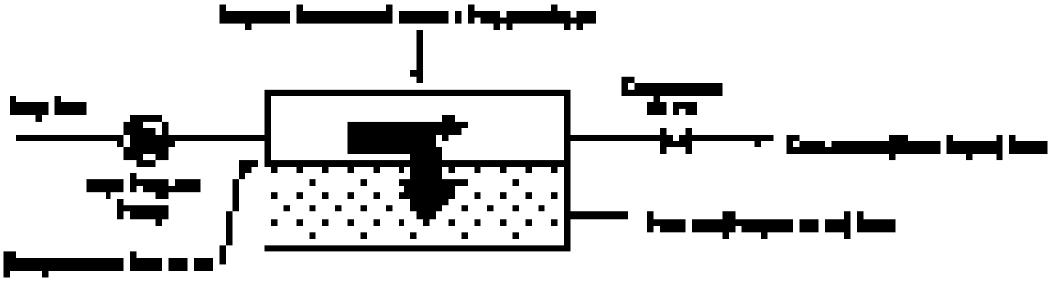
Figure 1: Overview of Osmosis / Reverse Osmosis

2.3.2
How to Use Reverse Osmosis in Practice

The simplified reverse osmosis process is shown in Figure 2.

With a high pressure pump, pressurized saline feed water is continuously pumped to the module system. Within the module, consisting of a pressure vessel (housing) and a membrane element, the feed water will be split into a low-saline product, called permeate and a high saline brine, called concentrate or reject. A flow regulating valve, called concentrate valve, controls the percentage of feedwater that is going to the concentrate stream and the permeate which will be obtained from the feed.

In the case of a spiral wound module consisting of a pressure vessel and several spiral wound elements, pressurized water flows into the vessel and through the channels between the spiral windings of the element. Up to seven elements are connected together within a pressure vessel. The feedwater becomes more and more concentrated and will enter the next element, and at last exits from the last element to the concentrate valve where the applied pressure will be released. The permeate of each element will be collected in the common permeate tube installed in the center of each spiral wound element and flows to a permeate collecting pipe outside of the pressure vessel.



$$\text{Recovery (\%)} = \frac{\text{Permeate Flow} \cdot 100}{\text{Feed Flow}}$$

$$\text{Salt Passage (\%)} = \frac{\text{Permeate Salt Concentration} \cdot 100}{\text{Feed Salt Concentration}}$$

$$\text{Salt Rejection (\%)} = 100 - \text{Salt Passage}$$

Figure 2: Reverse Osmosis Process

2.3.3
Reverse Osmosis Module Designs

Four basic types of RO module designs are in commercial use: tubular, plate-and-frame, spiral wound, and hollow fiber modules.

The tubular and the plate-and-frame devices date back to the early days of RO membrane technology. Both of these designs involve a high initial capital cost and a low membrane packing density (very low for the tubular design). However, these designs can operate on highly fouling feedwaters. Thus, these designs find use in the food industry (examples: milk concentration for cheese manufacture, tomato juice concentration), and in concentration/ treatment of wastewaters. They seldom compete with spirals and hollow fiber modules in desalination and water purification applications.

The design of spiral wound elements contains two layers of membrane glued back-to-back onto a permeate collector fabric (permeate channel spacer). This membrane envelope is wrapped around a perforated tube into which the permeate empties from the permeate channel spacer. A plastic netting is wound into the device, and maintains the feedstream channel spacing. It also promotes mixing of the feedstream to minimize concentration polarization.

The design of a hollow fiber permeator can package a tremendous amount of membrane area into a small volume. The difficulty in this approach, however, is that these fibers act almost like a string filter. This design requires a high level of feedwater pretreatment to minimize the fouling potential of the feedwater. And when they are fouled, they are very difficult to regenerate by cleaning methods. Another aspect of hollow fiber permeators is that abrasion through fiber-fiber contact or via fiber contact with trapped particles appears to occur during RO operation. This results in gradual fall-off of salt rejection with time.

Below is a set of comparisons between the four basic module designs. Comparing their susceptibility to fouling for example, hollow fiber devices are much worse than spiral wound devices, which in turn are much worse than tubular devices and plate-and-frame devices.

Comparisons of Reverse Osmosis System Types

System Costs:
Tubular, plate & frame >> hollow fiber, spiral

Flexibility in Design:
Spiral >> hollow fiber > plate & frame > tubular

Cleaning Behaviour:
Plate & frame > tubular > spiral > hollow fiber

System Space Requirements:
Tubular >> plate & frame > spiral > hollow fiber

Susceptibility to Fouling:
Hollow fiber >> spiral > plate & frame > tubular

Energy Requirement:
Tubular > plate & frame > hollow fiber > spiral

Referring to system costs, spiral wound and hollow fiber systems are relatively equal on well water sources. For surface water sources, pretreatment costs tend to be higher for hollow fiber systems because of their fouling potential. Tubular and plate-and-frame systems are far more expensive than hollow fiber and spiral wound devices, and are relatively cost competitive to each other.

As for system space requirements, tubular modules require the most space, hollow fiber and spiral modules require the least space.

One specific advantage of spiral wound units is that they can be linked together into series of two to seven elements within a single pressure vessel. Thus, up to seven times the flow of product water can be handled with only a single set of plumbing connections for feed, concentrate and permeate to a pressure vessel. In the case of hollow fiber modules, each hollow fiber unit requires installation of one feedwater inlet, one concentrate outlet, and one permeate outlet. For large modular systems for field application, a significant percentage of the system cost will be in the plumbing connections.

2.3.4
Factors Influencing Reverse Osmosis Performance

Permeate Flux[1] and salt rejection are the key performance parameters of a reverse osmosis process. They are mainly influenced by variable parameters which are as follows:

- pressure
- temperature
- recovery
- feed water salt concentration

The following graphs show the impact of each of those parameters when the other three parameters are kept constant. In practice, there is normally an overlap of two or more effects.

Not to be neglected are several main factors which cannot be seen directly in membrane performance. These are maintenance and operation of the plant as well as proper pretreatment design. Consideration of these three 'parameters', which have very strong impact on the performance of a reverse osmosis system, is a must for each OEM (original equipment manufacturer) and end user of such a system.

Pressure
With increasing effective feed pressure, the permeate TDS will decrease while the permeate flux will increase as shown in Figure 3.

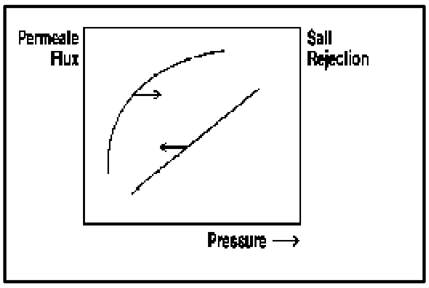


Figure 3: Performance vs. Pressure

Temperature
If the temperature increases and all other parameters are kept constant, the permeate flux and the salt passage will increase (see Figure 4).

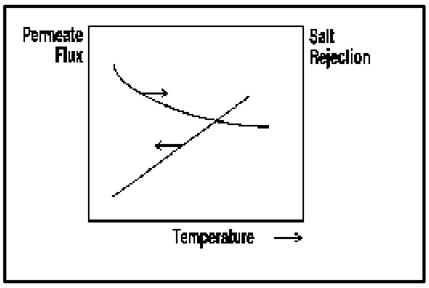


Figure 4: Performance vs. Temperature

Recovery
The recovery is the ratio of permeate flow to feed flow. In the case of increasing recovery, the permeate flux will decrease and stop if the salt concentration reaches a value where the osmotic pressure of the concentrate is as high as the applied feed pressure. The salt rejection will drop with increasing recovery (see Figure 5):

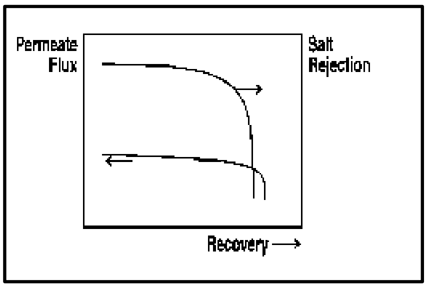


Figure 5: Performance vs. Recovery

Feedwater Salt Concentration
Figure 6 shows the impact of the feedwater salt concentration on the permeate flux and the salt rejection.

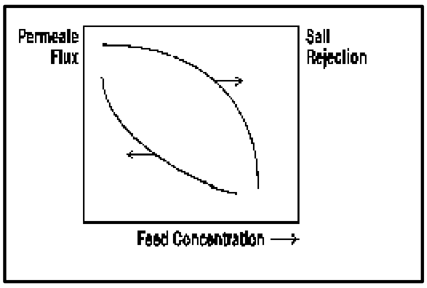


Figure 6: Performance vs. Feedwater Salt Concentration

Table 1 shows a summary of the impacts influencing reverse osmosis plant performance.

Table 1: Factors Influencing Reverse Osmosis Performance

Increasing	Permeate Flow	Salt Passage
Effective Pressure	↑	↓
Temperature	↑	↑
Recovery	↓	↑
Feed Salt Concentration	↓	↑

increasing ↑ decreasing ↓

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[1] **Permeate flow through unit membrane area (in l/m²h or GFD)**

2.4 FT30 Membrane Description

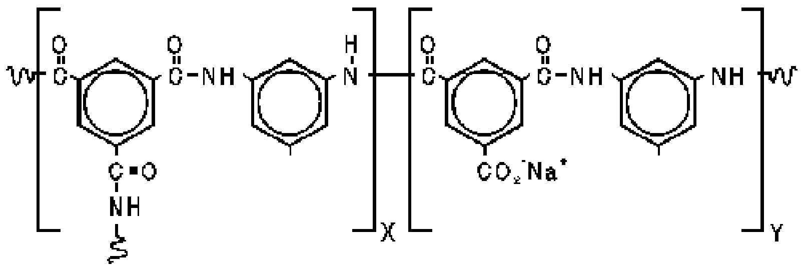
Composition of the FT30 membrane
The FILMTEC® FT30 thin film composite reverse osmosis membrane is made from one of the simplest aromatic diamines: 1,3-benzenediamine (meta phenylene diamine). The final chemical structure of the membrane is believed to be as shown in Figure 1.

Thin Film Composite Configuration
The FT30 membrane is defined as a thin film composite membrane consisting of three layers: a polyester support web, a microporous polysulfone interlayer, and an ultra thin barrier layer on the top surface. A schematic diagram of the membrane is shown in Figure 2.

The major structural support is provided by the non-woven web, which has been calendered to produce a hard, smooth surface free of loose fibers. Since the polyester web is too irregular and porous to provide a proper substrate for the salt barrier layer, a microporous layer of engineering plastic (polysulfone) is cast onto the surface of the web.

The polysulfone coating is remarkable in that it has surface pores controlled to a diameter of approximately 150 Angstroms. The FT30 barrier layer, about 2,000 Angstroms thick, can withstand high pressures because of the support provided by the polysulfone layer. Because of its barrier layer thickness, FT30 is very resistant to mechanical stresses and chemical degradation.

Figure 3 shows an SEM-photograph of a cross-section of the FILMTEC



FT30 polyamide is cross-linked and contains carboxylate groups

FT30 membrane.

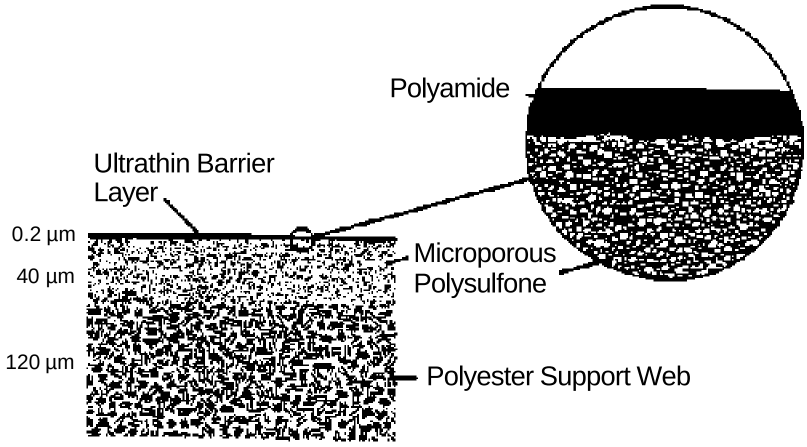


Figure 2: Schematic Cross-Section of Thin Film Composite Reverse Osmosis Membrane

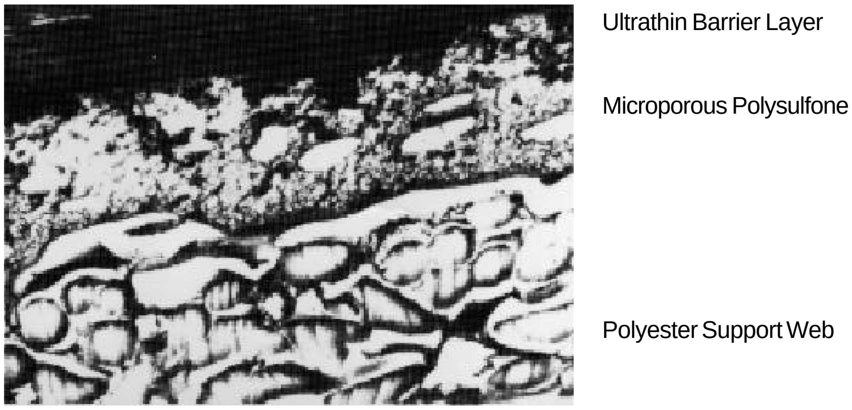


Figure 3: SEM Photograph of a Cross-Section of the FILMTEC FT30 Membrane

Figure 1: FILMTEC FT30 Membrane Structure

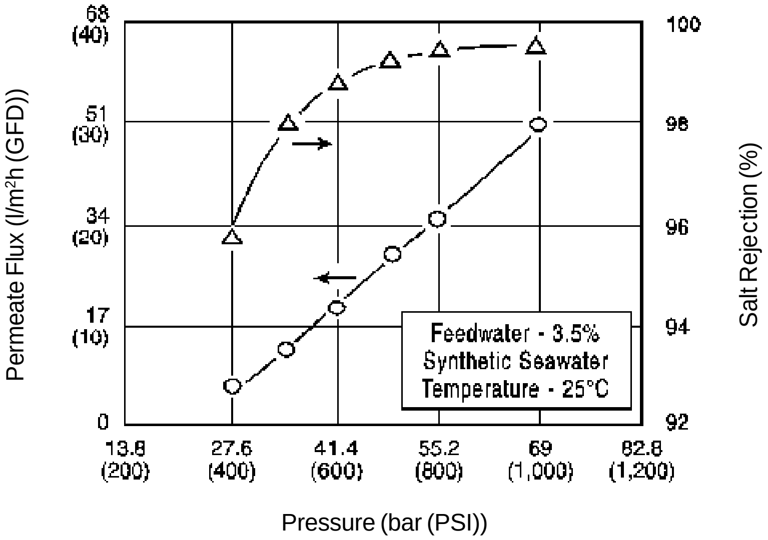
2.5 Membrane Specifications

FILMTEC® thin film composite reverse osmosis (RO) membranes give excellent performance for a wide variety of applications, including low-pressure tapwater use, single-pass sea water and brackish water desalination, chemical processing and waste treatment. This membrane exhibits excellent performance in terms of flux, salt rejection, and microbiological resistance. FILMTEC elements can operate over a pH range of 2 to 11, are resistant to compaction and are suitable for temperatures up to 45°C.

FILMTEC spiral wound elements have been extensively used since 1980. In numerous trials under actual sea water conditions, FT30 elements have provided salt rejections of better than 99.5% and fluxes of 24 l/m²h (14 GFD). On a 0.2% salt solution at 15.5 bar (225 PSI), rejections above 98% and fluxes of 40 l/m²h (24 GFD) are routinely obtained.

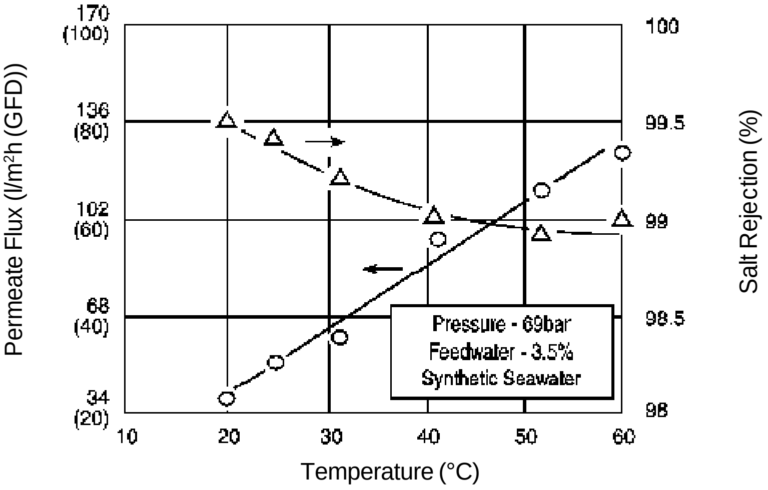
Figures 1 to 4 show the performance of the FT30 membrane (SW grade) vs. pressure, temperature, feedwater pH and feedwater salt concentration.

Typical solute rejections of FT30 membrane are shown in Table 1.



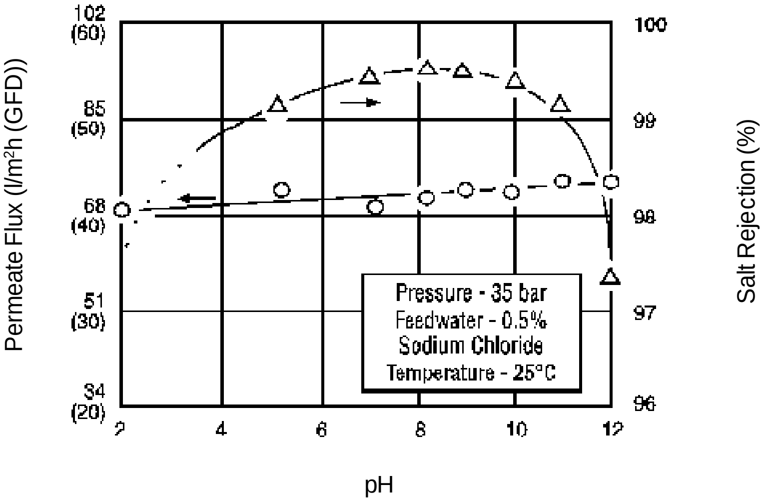
Results: Permeate flux increases linearly with pressure. Salt rejection reaches a plateau at about 60 l/m²h flux. Intercept at zero permeate flux is approximate osmotic pressure of feedwater.

Figure 1: Feedwater Pressure - Effect on FT30 Flux & Salt Rejection



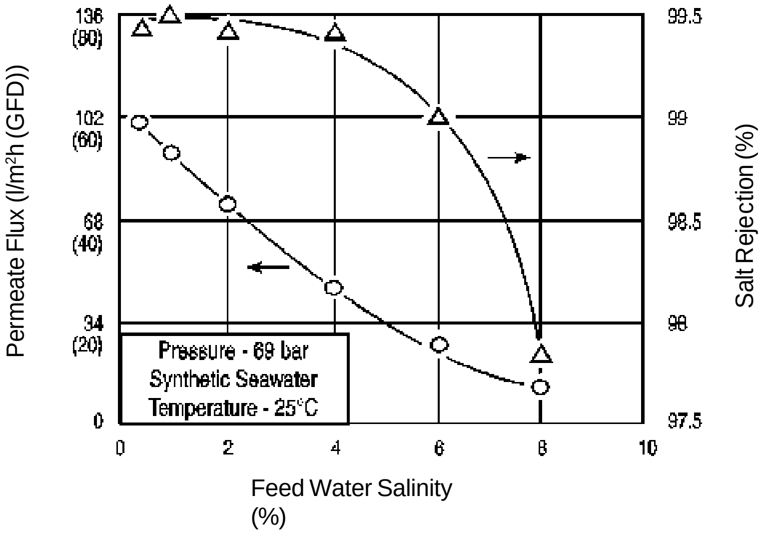
Results: Flux increases almost linearly with temperature. Salt rejection falls off with increasing temperature. Some hysteresis is evident in flux curves for temperature cycles (not shown) but not in salt rejection curves.

Figure 2: Feedwater Temperature - Effect on FT30 Flux & Salt Rejection



Results: Salt rejection and flux are rather constant over a broad pH range. Maximum salt rejection occurs at pH 8.5.

Figure 3: Feedwater pH - Effect on FT30 Flux & Salt Rejection



Results: Permeate flux will decrease as feedwater salinity increases. Salt rejection eventually also declines when permeate flux becomes insufficient.

Figure 4: Feedwater Concentration - Effect on FT30 Flux & Salt Rejection

Table 1: Typical Solute Rejections of FT30 Membrane

Solute	MW	Rejection (%) BW Grade	Rejection (%) SW Grade	Rejection (%) SW HR Grade
Sodium Fluoride NaF	42	99	>99	>99
Sodium Cyanide NaCN (pH 11)	49	97	98	99
Sodium Chloride NaCl	58	99	>99	>99
Silica SiO_2 (50 ppm)	60	98	99	>99
Sodium Bicarbonate $NaHCO_3$	84	99	98	99
Sodium Nitrate $NaNO_3$	85	97	96	98
Magnesium Chloride $MgCl_2$	95	99	>99	>99
Calcium Chloride $CaCl_2$	111	99	>99	>99
Magnesium Sulfate $MgSO_4$	120	>99	>99	>99
Nickel Sulfate $NiSO_4$	155	>99	>99	>99
Copper Sulfate $CuSO_4$	160	>99	>99	>99
Formaldehyde	30	35	50	60
Methanol	32	25	35	40
Ethanol	46	70	80	85
Isopropanol	60	90	95	97
Urea	60	70	80	85
Lactic Acid (pH 2)	90	94	97	98
Lactic Acid (pH 5)	90	99	>99	>99
Glucose	180	98	99	>99
Sucrose	342	99	>99	>99
Chlorinated Pesticides (traces)	-	>99	>99	>99

Standard Conditions

2,000 ppm Solute, 225 PSI Feed Pressure (1,6 MPa)
Feed Temperature 77°F (25°C), Feed pH 7 (unless otherwise noted)

As a general rule, the rejection of a solute increases from the BW grade to the SWHR grade membrane, and with the

- degree of dissociation
- ionic change
- molecular weight
- nonpolarity
- degree of molecular branching

of the considered chemical compound.

FDA has approved the Food Additive Petition covering the FT30 barrier layer
Under the food additive provision of the Federal Food, Drug and Cosmetic Act, contact surfaces of components used in the production of food, including water, must comply with established regulations set forth by the U.S. Food and Drug Administration (FDA) in order to receive approval for safe use. In accordance with its long-standing commitment to quality, petitions were submitted to the FDA for the FILMTEC® FT30 reverse osmosis membrane for evaluation and approval.

The procedure for FDA approval is rigorous and thorough. First, a food additive petition must be submitted to the FDA. This petition includes information about the chemical identity and composition of the component and its physical, chemical and biological properties. The petitioner must also describe the proposed use of the component, including all directions, recommendations and suggestions. Data must be included which establish that the component will have the intended effect when used in this manner. In addition, experimental data must show the extent that the component directly or indirectly affects the safety of the food with which it comes in contact. The petition must finally analyze the environmental impact of the manufacturing process and the ultimate use of the component.

The FDA evaluates the petition for the specific biological properties of the component and its demonstrated safety for the proposed use. The data and experimental methods are also evaluated for adequacy and reliability. As a guideline for this evaluation, the FDA uses the principles and procedures for establishing the safety of food additives stated in current publications of the Nation Academy of Sciences-National Research Council.

The Food Additive Petition concerning both FILMTEC membranes for use in processing liquid foods and purifying water for food applications received FDA approval. This approval is published in the Code of Federal Regulations under Title 21, Section 177.2550, Reverse Osmosis Membranes. The FT30 reverse osmosis membrane has been approved under the above procedure. The French Health Ministry has approved a Petition covering the BW30 reverse osmosis and NF70 nanofiltration membrane elements to be used in the drinking water production process.

The membrane elements were tested under the French procedure (static and dynamic conditions which simulate the real conditions) by an independent institute in France (Laboratoire d'Hygiene et de Recherches en Santé Publique = LHRSP).

Based on the test results the institute determined compliance with the French law on drinking water, which takes into account the European Community legislation on drinking water.
Then a dossier was submitted by the petitioner to the French Health Ministry including

- the above mentioned test results with the compliance statement
- composition of the membrane elements with references to whether the substances used in the manufacturing process are listed in the EC legislation on plastic materials intended to come into contact with foodstuffs
- a description of the manufacturing process
- the quality control system
- the disinfectant process for the membrane elements

The Petition concerning the FILMTEC BW30 reverse osmosis and NF70 nanofiltration membrane elements for use in drinking water production process has been approved by the French Health Ministry in an official letter dated 17 Nov. 1992 with the reference No. 2005 (NF70) and No. 2006 (BW30) under the above mentioned approval procedure.

2.6 FT30 – Spiral Wound Element

2.6.1
Introduction

FILMTEC® membranes are thin film composite membranes packed in a spiral wound configuration.
Spiral wound designs offer many advantages compared to other module designs, such as tubular-, plate and frame and hollow fiber module design for most of the reverse osmosis applications in water treatment. Typically, spiral wound configuration offers significantly lower replacement costs, simpler plumbing systems, easier maintenance and greater design freedom than other configurations.

2.6.2
Spiral Wound Element Configuration

The construction of a spiral wound FILMTEC RO membrane element as well as its installation in a pressure vessel is schematically shown in Figure 1.

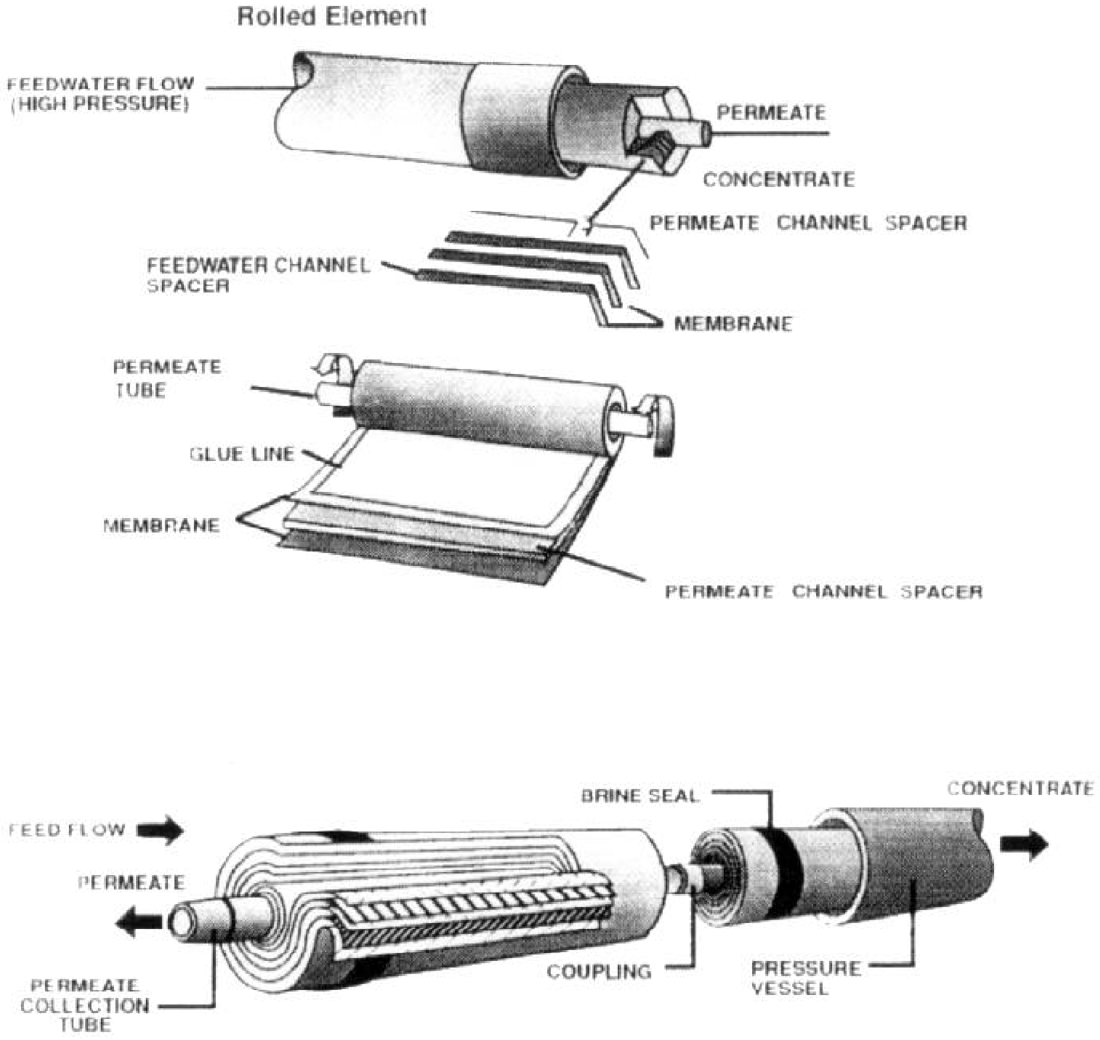


Figure 1: Construction of Spiral Wound FILMTEC RO Membrane Element

2.6.3 FILMTEC Element Characteristics

Element Types
The FILMTEC® membrane is classified in different types of elements, each selected and optimized with respect to the application and the needed conditions for it. There are four element types:

- TW30 - typically used for Tap Water
- BW30 - typically used for Brackish Water
- SW30 - typically used for Sea Water
- SW30HR - typically used for Sea Water and High Rejection

There are several element sizes: see Table 1.

The nomenclature of the elements is according to Table 2.

Element Performance
The performance of the four types of elements is different and depends on applied feed pressure and used element dimensions.

The table on the following page shows the whole list of FILMTEC reverse osmosis elements with physical characteristics, operating limits and standard conditions.

Table 1: FILMTEC Element Types

Element Type	Diameter inch	Permeate Flow [1] at Standard Test Conditions [2] l/h	(GPD)	Maximum Operating Pressure bar	(PSI)
TW30	1.5-1.8	1.6-7.9	(10-50)	8.6	(125)
	2.0-4.0	16-442	(100-2,800)	21	(300)
	4.6	106-410	(675-2,600)	41	(600)
BW30	2.5-4.0-8.0	24-2240	(150-14,200)	41	(600)
SW30	2.5-4.0-8.0	16-946	(100-6,000)	69	(1,000)
SW30HR	2.5-4.0-8.0	10-631	(65-4,000)	69	(1,000)

[1] Varying with different element dimensions

[2] Standard Test Conditions:

	Feedwater	Temp. °F	(°C)	Feed Pressure bar	(PSI)
TW30 ≤ 1.8"	Tapwater, TDS=250 ppm	77	(25)	3.45	(50)
TW30 ≥ 2" BW30	2,000 ppm NaCl	77	(25)	15.5	(225)
SW30	Sea Water, TDS=35,000 ppm	77	(25)	55	(800)
SW30HR	32,000 ppm NaCl	77	(25)	55	(800)

Table 2: Element Nomenclature

The element nomenclature for FILMTEC elements is for example as follows:

TW 30 - 40 40
40 – Length of Element in inches
40 – Diameter of Element, divided by 10, in inches
30 – FT30 - Element Family
TW – TW - Tap Water
BW - Brackish Water
SW - Sea Water
SWHR - Sea Water High Rejection

At times the membrane surface area is used in place of diameter and length (i.e. BW30-400).

3. Water Chemistry and Pretreatment

3.1 Introduction

To increase the efficiency and life of a reverse osmosis system, effective pretreatment of the feed water is required. Selection of the proper pretreatment will maximize efficiency and membrane life by minimizing:

- Fouling
- Scaling
- Membrane degradation

The net result of the above will be the optimization of:

- Product flow
- Salt rejection
- Product recovery
- Operating costs

For the purpose of this manual, “fouling” will refer to the entrapment of particulates such as iron floc or silt, whereas “scaling” will refer to the precipitation and deposition within the system of sparingly soluble salts such as calcium sulfate ($CaSO_4$) or barium sulfate ($BaSO_4$).

Pretreatment of feed water must involve a total system approach for continuous and reliable operation. For example, an improperly designed and/or operated clarifier will result in loading the sand or multimedia filter beyond its operating limits. Such inadequate pretreatment often necessitates frequent cleaning of the elements to restore productivity and salt rejection. The cost of cleaning, downtime, and lost system performance can be significant.

The proper treatment scheme for the feed water will depend on:

- Feed water source
- Feed water composition
- Application

The type and extent of a pretreatment system will depend to a large extent on whether the feed water source is well water or surface water. In general, well water is a consistent feed source which has a low Silt Density Index (SDI) (typically < 2) and low bacteria count. Well water typically requires a very simple pretreatment scheme such as acid addition, inhibitor addition, and a 5 µm cartridge filter.

Surface water, on the other hand, is a variable feed water source which is affected by seasonal factors. It is also characterized by a high SDI and can have a high bacteria count. Pretreatment for surface water is more elaborate than pretreatment for well water. Additional pretreatment steps often include polymer addition, clarification, and multimedia filtration.

Once the feed water source has been determined, a complete and accurate analysis of the feed water should be made. The importance of this feed water analysis cannot be over emphasized. It is critical in determining the proper pretreatment and RO system design.

Finally, the application often determines the type or extent of reverse osmosis pretreatment. For example, pretreatment in an electronics application might be much more sophisticated than for a municipal system due to the different product water quality requirements.

3.2 Feed Water Analysis

The major water types being treated by RO are:

- Low salinity brackish waters with Total Dissolved Solids (TDS) of up to 5,000 ppm.
- High salinity brackish waters with TDS in the range of 5,000 - 15,000 ppm.
- Sea water with TDS in the range of 35,000 ppm.

Sea water with TDS of 35,000 mg/l is considered as “standard sea water” as this constitutes by far the largest amount of water worldwide. The composition is nearly the same all over the world (see Table 1). The actual TDS content may, however, vary within wide limits from e.g. the Baltic Sea with 7,000 mg/l to the Red Sea and Arabian Gulf with up to 45,000 mg/l. The actual compositions can be proportionally estimated from the “standard sea water” composition.

Be aware that seashore wells depending on the soil, influx from inland, etc. can often have salinity and composition quite different from that of a sample taken from the sea itself.

In sea water treatment the limiting factor is of a physical nature, i.e. the osmotic pressure caused by the high TDS.

In brackish water treatment the limiting factor is mostly of a chemical nature, i.e. precipitation and scale formation by e.g. calcium carbonate or sulfate. The composition of brackish waters is of extremely wide variation, and a water analysis is a must for a good process design.
Two examples of brackish water analysis are given in Table 2.

Table 1: “Standard Sea Water” Composition

Ion	Concentration (mg/l)	Ion	Concentration (mg/l)
Calcium	410	Silica	0.04-8
Magnesium	1,310	Chloride	19,700
Sodium	10,900	Sulfate	2,740
Potassium	390	Fluoride	1.4
Barium	0.05	Bromide	65
Strontium	13	Nitrate	< 0.7
Iron	< 0.02	Bicarbonate	152
Manganese	< 0.01		
	TDS	35,000 mg/l	
	pH	8.1	

Table 2: Brackish Water Composition (Examples)

		1	2
Calcium	mg/l	265	75
Magnesium	mg/l	106	9
Sodium	mg/l	530	75
Potassium	mg/l	14	6
Iron	mg/l	0.19	0.5
Manganese	mg/l	< 0.01	0.4
Barium	mg/l	0.03	0.09
Strontium	mg/l	10	2
Ammonium	mg/l	< 0.1	0.4
Chloride	mg/l	1,025	120
Bicarbonate	mg/l	350	220
Sulfate	mg/l	540	45
Nitrate	mg/l	23	0.7
Fluoride	mg/l	0.4	0.1
Phosphate	mg/l	< 1	0.7
Silica	mg/l	4.1	7
TDS	mg/l	2,760	562
TOC	mg/l	0.3	1.0
pH	1	7.1	7.6
Conductivity	mS/m	430	70
Temperature	°C	29	15

Before a projection of a reverse osmosis system design can be run, a complete and accurate water analysis must be provided. A water analysis form (see Table 3) must be completed and balanced to electroneutrality, i.e., anion and cation concentrations must be identical when stated in terms of the calcium carbonate equivalent. In case the water analysis is not in balance we recommend adding either Na^+ or Cl^- in order to achieve electroneutrality.

Table 3: Water Analysis for Reverse Osmosis

Sample identification: ....

Feed source: ....

Conductivity: .... pH: .... Temperature (°C): ....

Feed water analysis [1]:

NH_4^+ : ....
K^+ : ....
Na^+ : ....
Mg^{++} : ....
Ca^{++} : ....
Ba^{++} : ....
Sr^{++} : ....
Fe^{++} : ....
Fe (tot) : ....
Mn^{++} : ....

CO_2 : ....
CO_3^{--} : ....
HCO_3^- : ....
NO_3^- : ....
Cl^- : ....
F^- : ....
SO_4^{--} : ....
PO_4^{--} : ....
S^{--} : ....
SiO_2 (colloidal) : ....
SiO_2 (soluble) : ....

Other ions: ....

TDS (by method): ....
TOC: ....
BOD: ....
COD: ....

Total alkalinity (m-value): ....
Carbonate alkalinity (p-value): ....
Total hardness: ....
Turbidity (NTU): ....
Silt density index (SDI): ....
Bacteria (count/ml): ....
Free chlorine: ....

Remarks: ....
(odor, smell, color, biological activity, etc.:) ....
....
....

Analysis by: ....

Date: ....

---

[1] Please give units (mg/l as ion or ppm as $CaCO_3$ or meq/l)

Ba^{++} and Sr^{++} must be analyzed at the 1 µg/l (ppb) and 1 mg/l (ppm) level of detection respectively, before a reverse osmosis system design can be finalized. Also, if iron is present above 0.5 mg/l (ppm) in the feed water, pretreatment must be implemented to reduce it below that level.

It is important that the temperature be given as a range rather than an absolute temperature. Temperature variation can impact the scaling potential of a reverse osmosis system, especially when silica levels in the feed water are high.

After the reverse osmosis system is in service, the reverse osmosis feed water should be analyzed on a weekly basis. If more than a 10% increase is seen in any constituents (anion or cation), particularly detrimental ones, the new analysis should be resubmitted to Dow or a qualified OEM so that new operating limits can be computed.

If the feed water analysis shows constant values the analysis may be executed on a monthly basis.

Many standards are available for unifying water analysis techniques. As a minimum, Dow supports the use of the Standard Methods for the Examination of Water and Waste Water (most recent edition) as published jointly by the American Public Health Association / the American Water Works Association and the Water Pollution Control Federation (Endorsement of these Standards does not constitute any criticism or value judgement against other national or professional standards on behalf of The Dow Chemical Company).

Another excellent guide is the “German standard methods for the examination of water, waste water and sludge.”

A “Standard Guide for Water Analysis for Reverse Osmosis Application” is given in ASTM Standard D4195-88 in the Annual Book of ASTM Standards, Vol. 11 – Water. This guide is applicable to waters including brackish waters and sea waters. A listing of the relevant ASTM procedures is given in Table 4.

Table 4: ASTM Procedures Relevant to Water Analysis for Reverse Osmosis Application

D511 - Calcium and Magnesium
D512 - Chloride
D513 - Carbon Dioxide, Bicarbonate, Carbonate
D515 - Phosphorus
D516 - Sulfate
D857 - Aluminium
D858 - Manganese
D859 - Silica
D888 - Dissolved Oxygen
D1068 - Iron
D1179 - Fluoride
D1253 - Residual Chlorine
D1293 - pH
D1428 - Potassium and Sodium by Flame Photometry
D1888 - Particulate and Dissolved Matter
D1889 - Turbidity
D2579 - Total and Organic Carbon
D3352 - Strontium
D3370 - Practices for Sampling Water
D3561 - Lithium, Potassium, Sodium by AAS
D3867 - Nitrite - Nitrate
D4189 - Silt Density Index
D4382 - Barium
F60 - Microbiological Contaminants in Water

3.3 Scale Control

3.3.1
Introduction

Scaling of a reverse osmosis membrane may occur when sparingly soluble salts are concentrated within the element beyond their solubility limit. For example, if a reverse osmosis plant is operated at 50% recovery, the concentration in the concentrate stream will be double the concentration in the feed stream. As the recovery of a plant is increased, so is the risk of scaling.Therefore, care must be taken not to exceed the solubility limits of slightly soluble salts, or precipitation and scaling may occur.

In a reverse osmosis system the most common sparingly soluble salts encountered are $CaSO_4$, $CaCO_3$ and silica. Other salts creating a potential scaling problem are CaF_2, $BaSO_4$ and $SrSO_4$. Solubility products of sparingly soluble inorganic compounds are listed in Table 1.

In order to prevent scaling of a reverse osmosis membrane the following design practices are possible.

3.3.2
Acid Addition

Most natural surface and ground waters are almost saturated with respect to $CaCO_3$. The solubility of $CaCO_3$ depends on the pH, as can be seen from the following equation:

$$Ca^{++} + HCO_3^{-} \leftrightarrow H^{+} + CaCO_3 \qquad (1)$$

Accordingly, by adding H^+ as acid, the equilibrium can be shifted to the left side in order to keep calcium carbonate dissolved. The acid used should be of food grade quality.

Table 1: Solubility Products of Sparingly Soluble Inorganic Compounds[1]

Substance	Formula	Temp. °C	Solubility Product	Negative Log K
Aluminium Hydroxide	$Al(OH)_3$	20	1.9×10^{-33}	32.7
Barium Carbonate	$BaCO_3$	16	7×10^{-9}	8.15
Barium Sulfate	$BaSO_4$	25	1.08×10^{-10}	9.97
Calcium Carbonate	$CaCO_3$	25	8.7×10^{-9}	8.06
Calcium Fluoride	CaF_2	26	3.95×10^{-11}	10.61
Calcium Sulfate	$CaSO_4$	10	6.1×10^{-5}	4.21
Cupric Sulfide	CuS	18	8.5×10^{-45}	44.07
Ferric Hydroxide	$Fe(OH)_3$	18	1.1×10^{-36}	35.96
Ferrous Hydroxide	$Fe(OH)_2$	18	1.64×10^{-14}	13.78
Lead Carbonate	$PbCO_3$	18	3.3×10^{-14}	13.48
Lead Fluoride	PbF_2	18	3.2×10^{-6}	7.50
Lead Sulfate	$PbSO_4$	18	1.06×10^{-8}	7.98
Magnesium Ammonium Phosphate	$MgNH_4PO_4$	25	2.5×10^{-13}	12.6
Magnesium Carbonate	$MgCO_3$	12	2.6×10^{-5}	4.58
Magnesium Hydroxide	$Mg(OH)_2$	18	1.2×10^{-11}	10.92
Manganese Hydroxide	$Mn(OH)_2$	18	4×10^{-14}	13.4
Nickel Sulfide	NiS	18	1.4×10^{-24}	23.85
Strontium Carbonate	$SrCO_3$	25	1.6×10^{-9}	8.80
Strontium Sulfate	$SrSO_4$	17.4	2.81×10^{-7}	6.55
Zinc Hydroxide	$Zn(OH)_2$	20	1.8×10^{-14}	13.74

[1] At zero ionic strength

Sulfuric acid is easier to handle and in many countries more readily available than hydrochloric acid, but on the other hand, additional sulfate is added to the feed stream. This might be critical with respect to sulfate scaling (sections 3.4.3 to 3.4.5).

In order to avoid calcium carbonate scaling, $CaCO_3$ should tend to dissolve in the concentrate stream rather than to precipitate. This tendency can be expressed by the Langelier Saturation Index (LSI) for brackish waters and the Stiff & Davis Stability Index (S&DSI) for sea waters. At the pH of saturation (pH_S), the water is in equilibrium with $CaCO_3$.

The definitions of LSI and S&DSI are:

$$LSI = pH - pH_S \quad (TDS < 10{,}000\ mg/l) \qquad (2)$$

$$S\&DSI = pH - pH_S \quad (TDS > 10{,}000 mg/l) \qquad (3)$$

To control calcium carbonate scaling by acid addition alone, the LSI or S&DSI in the concentrate stream must be negative. If a high quality scale inhibitor is used, the LSI in the concentrate stream can be ≤ 1.5. This will reduce or eliminate the acid consumption. Many inhibitors allow operation up to an LSI of < 1.8 in the concentrate. Please refer to the inhibitor manufacturer's own literature for reference points.

3.3.3
Scale Inhibitor Addition

Scale inhibitors (antiscalants) can be used to control carbonate scaling, sulfate scaling and calcium fluoride scaling.

Scale inhibitors have a “threshold effect”, which means that minor amounts adsorb specifically to the surface of microcrystals thereby preventing further growth and precipitation of the crystals. The most widely used scale inhibitor is sodiumhexametaphosphate (SHMP). Food grade quality should be used. Care has to be taken in order to avoid hydrolysis of SHMP in the dosing feed tank. Hydrolysis would not only decrease the scale inhibition efficiency, but also create a calcium phosphate scaling risk.

SHMP should be dosed to give a concentration in the concentrate stream of 20 mg/l. For example, the dosage into the feed stream of a system with 75% recovery will be 5 mg/l.

Polymeric organic scale inhibitors are more effective than SHMP. However, precipitation reactions may occur with cationic polyelectrolytes or multivalent cations, e.g. aluminium or iron. The resulting gumlike products are very difficult to remove from the membrane elements.

For dosage rates please contact the antiscalant manufacturers. Overdosing should be avoided.
In RO plants operating on sea water with TDS in the range of 35,000 mg/l, scaling is not such a problem as in brackish water plants, because the recovery of sea water plants is limited by the osmotic pressure of the concentrate stream to 30-45%. However, for safety reasons we recommend using a scale inhibitor when operating above a recovery of 35%.

Table 2: FT30 Compatible Antiscalant

FT30 Compatible Antiscalant	Supplier	Minimum Concentration in Dilution Tank
AF 100	BF Goodrich	
AF 400	BF Goodrich	
AF 600	BF Goodrich	
AF 800 (60 ppm max)	BF Goodrich	0.5 %
AF 1000	BF Goodrich	5 %
ARRO-TREAT 1100	Arrowhead	5 %
ARRO-TREAT 1200	Arrowhead	0.5 %
ARRO-TREAT 1300	Arrowhead	5 %
Betz 602 (15 ppm max)	Betz	0.75 %
Betz 605	Betz	10 %
Betz 606 (36 ppm max)	Betz	10 %
COATEX EM201ASP (20 ppm max)	Coatex	15 %
D8062 (20 ppm max)	Grace Dearborn	50 %
Dearborn 8563	Grace Dearborn	
Dequest 2054	Monsanto	
Drew 11-428 (36 ppm max)	Drew	10 %
Drewsperse 770	Drew	10 %
Ecolosperse	Ecolochem	10 %
EL 4010	Calgon	
EL 5500	Calgon	
EL 5600	Calgon	
Flocon 100	FMC	
Flocon 135	FMC	
Flocon 200 (20 ppm max)	FMC	5 %
Flocon 385	FMC	
Flomate 5405	Grace Dearborn	10 %
Flomate 5406 (36 ppm max)	Grace Dearborn	10 %
Flomate 5407	Grace Dearborn	
HYPER-Sperse	Argo Scientific	
IPC 5986	Chemlink	10 %
Kemazur 2120	Degremont	10 %
N-7295	Nalco	25 %
N-7306	Nalco	25 %
NALCO 2843	Nalco	10 %
Permatreat 471	Houseman	10 %
Permatreat 475 (36 ppm max)	Houseman	10 %
POLYACRYL PT115A (20 ppm max)	Polyacryl	15 %
Pretreat 110 (20 ppm max)	King-Lee	1 %
Pretreat Plus	King-Lee	
Sludgex 692	Maxwell Chemicals	10 %
Sludgex 693 (36 ppm max)	Maxwell Chemicals	10 %
Sodiumhexametaphosphate (SHMP)	-	
SP-2946	Petrolite Ltd.	10 %
SP-2948 (36 ppm max)	Petrolite Ltd.	10 %

The antiscalants listed in Table 2 have been tested for at least 1,000 hours in contact with an element at typical operating conditions without any negative effect on the membrane. They can be considered compatible with FILMTEC® membranes up to 50 ppm concentration in the concentrate (unless otherwise stated). The efficacy of these products has not been tested.
RO permeate should be used when diluting the antiscalant. Calcium present in untreated water may form a precipitate with the antiscalant at high antiscalant concentrations. Precautions must also be taken so that there is no microbiological growth in the antiscalant dilution tank. In order for the biocide present in the antiscalant to be effective, the antiscalant must not be diluted more than indicated in Table 2. Cationic polymers (e.g. polyelectrolytes) may coprecipitate with negatively charged antiscalants and foul the membrane. Make certain that no significant amounts of cationic polymers are present when adding an anionic antiscalant.

3.3.4
Softening with a Strong Acid Cation Exchange Resin

The scale forming cations such as Ca^{++}, Ba^{++}, Sr^{++} are removed and replaced by sodium cations. The resin has to be regenerated with NaCl at hardness breakthrough. The pH of the feed water is not changed by this treatment. Therefore, no degassifier is needed. Only a little CO_2 from the raw water is present that can pass into the permeate creating a conductivity increase there. One can even lower the permeate con-ductivity by adding some NaOH to the softened feed water (up to pH 8.2) in order to convert residual carbon dioxide into bicarbonate which is then rejected by the membrane. The rejection perfor-mance of the FT30 membrane is optimal at the neutral pH range.

With DOWEX* ion exchange resins, the removal efficiency for Ca^{++}, Ba^{++} and Sr^{++} is > 99.5%, which usually eliminates any risk of carbonate or sulfate scaling.

Softening with a strong acid cation exchange resin is very effective and safe, provided the regeneration is done properly.

It is used mainly in small or medium size brackish water plants, but not in sea water plants.

A drawback of this process is its relatively high sodium chloride consumption, which might cause an environmental or an economic problem. With DOWEX* MONOSPHERE* ion exchange resins and a countercurrent regeneration technique, for example UPCORE*, it is possible to minimize the sodium chloride consumption to 110% of the stoichiometrical value.

3.3.5
Dealkalization with a Weak Acid Cation Exchange Resin

Dealkalization with a weak acid cation exchange resin is used mainly in large brackish water plants for partial softening in order to minimize the consumption of regeneration chemicals.

In this process, only Ca^{++}, Ba^{++} and Sr^{++} linked to bicarbonate (temporary hardness) are removed and replaced by H^+, thus lowering the pH to 4-5. As the acidic groups of the resin are carboxylic groups, the ion exchange process stops when the pH reaches a value of 4.2, where the carboxylic groups are no longer dissociated. Therefore, it is only a partial softening. Only those scale forming cations are removed which are bound to bicarbonate. Therefore, this process is ideal for waters with a high bicarbonate content. The bicarbonate is converted into carbon dioxide:

$$HCO_3^- + H^+ \leftrightarrow H_2O + CO_2 \qquad (4)$$

In most cases, carbon dioxide is not desired in the permeate. It can be removed by degassing either in the permeate or in the feed stream.

Degassing the permeate is favored where a potential for biofouling is suspected (surface waters, high TOC, high bacteria counts). A high CO_2 concentration on the membranes helps to keep bacteria growth low. Degassing the feed is preferred when optimum salt rejection is the priority. Removing CO_2 also leads to an increase in pH (see equation (4)), and at pH > 6 the rejection is better than at pH < 5.

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The **advantages** of dealkalizing with a weak acid cation exchange resin are:

- For regeneration, acid of not more than 105% of the stoichiometrical value is needed. This minimizes the operating costs and the environmental impact.
- The TDS value of the water is reduced by the removal of bicarbonate salts. Accordingly, the permeate TDS value is also lower.

The **disadvantages** are:

- Residual hardness.

  If a complete softening is required, a sodium exchange process with a strong acid cation exchange resin can be added, even in one vessel. The overall consumption of regeneration chemicals is still lower than softening with a strong acid cation exchange resin alone. Due to the higher investment costs however, this combination will only be attractive for plants with high capacity.

  Another possibility to overcome this drawback of incomplete
  softening is to dose an antiscalant into the dealkalized water. Al-though we have so far never encountered scaling problems with waters dealkalized by weak acid cation exchange alone, we strongly recommend to calculate the solubilities of the residual sparingly soluble salts and to take the respective measures.
- Variable pH of the treated water.

  The pH of the dealkalized water ranges from 3.5 to 6.5 depending on the degree of exhaustion of the resin. This cyclic pH variation makes it difficult to control the salt rejection of the plant. At pH < 4.2, the passage of mineral acid may increase the permeate TDS. It is therefore recommended to use more than one filter in parallel and to regenerate them at different times in order to level out the pH. Other possibilities to avoid extremely low pH values are CO_2 removal or pH adjustment by NaOH afterwards.

3.3.6
Lime Softening

Lime softening can be used to remove carbonate hardness by adding hydrated lime:

$Ca(HCO_3)_2 + Ca(OH)_2 \rightarrow 2$
$CaCO_3 + 2\ H_2O$
(5)

$Mg(HCO_3)_2 + 2\ Ca$
$(OH)_2 \rightarrow Mg(OH)_2 + 2$
$CaCO_3 + 2H_2O$
(6)

The noncarbonate calcium hardness can be further reduced by adding sodium carbonate (soda ash):

$CaCl_2 + Na_2CO_3 \rightarrow 2$
$NaCl + CaCO_3$
(7)

The lime-soda ash process can also be used to reduce the silica concentration. When sodium aluminate and ferric chloride are added, the precipitate will include calcium carbonate and a complex with silicic acid, aluminium oxide and iron.

With the hot lime silicic acid removal process at 60-70°C, silica can be reduced to 1 mg/l by adding a mixture of lime and porous magnesium oxide.

With lime softening, barium, strontium and organic substances are also reduced significantly. The process requires a reactor with a high concentration of precipitated particles serving as crystallization nuclei. This is usually achieved by upflow solids-contact clarifiers. The effluent from this process needs media filtration and pH adjustment prior to the RO elements. Iron coagulants with or without polymeric flocculants (anionic and non-ionic) may be used to improve the solid-liquid separation.

Lime softening should be considered for brackish water plants larger than 200 m^3/h (880 gpm). More details are described in the literature [1) 2) 3)].

3.3.7
Preventive Cleaning

In some applications, scaling is controlled by preventive membrane cleaning. This allows the system to run without softening or dosage of chemicals. Typically, those systems operate at low recovery in the range of 25%, and the membrane elements are replaced after 1-2 years. Accordingly, those systems are mainly small single-element plants for potable water from tap water or sea water. The simplest way of cleaning is a forward flush at low pressure by opening the concentrate valve. Short cleaning intervals are more effective than long cleaning times, e.g. 30 seconds every 30 minutes.

Cleaning can also be carried out with cleaning chemicals as described in Section 8. In batch processes like in waste water treatment it is common practice to clean the membranes after every batch.

The cleaning procedure, cleaning chemicals and the frequency of cleaning, has to be determined and optimized case by case. Special care has to be taken not to allow a scaling layer to develop in the course of time.

3.3.8
Adjustment of Operating Variables

When other scale control methods do not work, the operating variables of the plant have to be adjusted in such a way that scaling will not occur. The precipitation of dissolved salts can be avoided by keeping their concentration below the solubility limit, that means by reducing the system recovery until the concentrate concentration is low enough.

Solubility depends also on temperature and pH. In the case of silica, increasing temperature and pH increases its solubility (see Section 3.4.7). Silica is usually the only reason for considering adjustment of operating variables as a scale control method, because these adjustments have economic drawbacks (energy consumption) or other scaling risks ($CaCO_3$ at high pH).

For small systems, a low recovery combined with a preventive cleaning program might be a convenient way to control scaling.

3.4 Scaling Calculations

3.4.1
General

Scaling calculations have to be carried out in order to determine whether a sparingly soluble salt presents a potential scaling problem in a reverse osmosis system. The calculation procedures described in Section 3.4, Scaling Calculations, are adapted from the corresponding ASTM Standards, cited in the References. To determine the scaling potential, one has to compare the ion product IP_c of the considered salt in the concentrate stream, with the solubility product K_{sp} of that salt under conditions in the concentrate stream. Generally, if $IP_c < K_{sp}$, no scale control measures have to be taken.

The ion product IP of a salt A_mB_n is defined as

$$IP = [A]^m[B]^n \qquad (1)$$

with [A] and [B] being the molal concentrations of the corresponding ions. For the concentration ranges present in RO applications, molal concentrations (mol/kg) can be considered equivalent with molar concentrations (mol/l).

The concentration of ion species in the concentrate stream is usually not known, but can easily be estimated from the concentration in the feed stream by multiplication with the concentration factor CF. The concentration factor is derived from the recovery Y (expressed as a decimal):

$$CF = 1 / (1 - Y) \qquad (2)$$

The solubility product K_{sp} is generally also expressed in molal concentrations and is dependent on ionic strength and temperature as shown in the Figures of this section 3.4.

The temperature in the concentrate stream is about the same as in the feed stream.

The ionic strength of the feed water is:

$$I_f = \frac{1}{2} \; \Sigma \, (m_i \times z_i^2) \qquad (3)$$

where:

m_i = molal concentration of ion i (mol/kg)
z_i = ionic charge of ion i

Where the water analysis is not given in molal (or molar) concentrations, the conversion is as follows:

$$m_i = \frac{c_i}{1{,}000 \, MW_i} \qquad (4)$$

where:
c_i = concentration of ion i, in mg/l
MW_i = molecular weight of ion i

Having calculated the ionic strength I_f of the feed stream with equation (3), the ionic strength I_c of the concentrate stream is obtained from:

$$I_c = I_f \times \frac{1}{1-Y} \qquad (5)$$

With the ionic strength of the concentrate stream, the solubility product K_{sp} of scaling salt can be obtained (see the following sections).

Calculation example of the ionic strength of the concentrate (I_c):

Feed Water Analysis

	mg/l	mol/l	(mol/kg)
Ca^{++}	200	5.0	$x\,10^{-3}$
Mg^{++}	61	2.51	$x\,10^{-3}$
Na^{+}	388	16.9	$x\,10^{-3}$
HCO_3^{-}	244	4.0	$x\,10^{-3}$
SO_4^{--}	480	5.0	$x\,10^{-3}$
Cl^{-}	635	17.9	$x\,10^{-3}$

The ionic strength I_f of the feed water is

$$I_f = 1/2\,([Ca^{++}] + [Mg^{++}] + [SO_4^{--}]) \times 4 + ([Na^{+}] + [HCO_3^{-}] + [Cl^{-}])$$

$$= 1/2\,((5.0 + 2.51 + 5.0) \times 10^{-3} \times 4 + (16.9 + 4.0 + 17.9) \times 10^{-3})$$

$$I_f = 0.0444$$

With a recovery of, for example, 75% (Y=0.75), the ionic strength of the concentrate becomes

$$- \quad - \quad \frac{1}{1 - 0.75}$$

$$I_c = 0.178$$

3.4.2 Calcium Carbonate Scale Prevention

3.4.2.1 Brackish Water

For brackish waters with TDS < 10,000 mg/l in the concentrate stream, the Langelier Saturation Index (LSI) is used to express the scaling potential for calcium carbonate.

The following data are needed to calculate the LSI of the concentrate stream (LSI_c):

Ca_f = Calcium concentration in feed, as $CaCO_3$, mg/l

TDS_f = Concentration of total dissolved solids in the feed, mg/l

Alk_f = Alkalinity in feed, as $CaCO_3$, mg/l

pH_f = pH of the feed solution

T = Temperature of the feed solution

Y = Recovery of the reverse osmosis system, expressed as a decimal

Calculation

a. Calculate the calcium concentration in the concentrate stream, Ca_c, as $CaCO_3$ in mg/l:

$$Ca_c = Ca_f \times \frac{1}{1-Y} \qquad (6)$$

b. Calculate the total dissolved solids in the concentrate stream, TDS_c in mg/l:

$$TDS_c = TDS_f \times \frac{1}{1-Y} \qquad (7)$$

c. Calculate the alkalinity in the concentrate stream, Alk_c, as $CaCO_3$ in mg/l:

$$Alk_c = Alk_f \times \frac{1}{1-Y} \qquad (8)$$

d. Calculate the free carbon dioxide content (C) in the concentrate stream by assuming that the CO_2 concentration in the concentrate is equal to the CO_2 concentration in the feed: $C_c = C_f$. The concentration of free carbon dioxide in the feed solution is obtained from Figure 1 as a function of the alkalinity and the pH of the feed solution.

e. Calculate the pH of the concentrate stream (pH_c) using the ratio of alkalinity Alk_c to free CO_2 in the concentrate, Figure 1.

f. From Figure 2 obtain: pCa as a function of Ca_c, pAlk as a function of Alk_c, "C" as a function of TDS_c and temperature (temperature of concentrate is assumed equal to temperature of feed solution).

g. Calculate pH at which concentrate stream is saturated with $CaCO_3$ (pH_s) as follows:

$$pH_s = pCa + pAlk + \text{“C”} \qquad (9)$$

h. Calculate the Langelier Saturation Index of the concentrate (LSI_c) as follows:

$$LSI_c = pH_c - pH_s \qquad (10)$$

Adjustments of LSI_c

In most natural waters, the LSI_c would be positive without pretreatment. To control $CaCO_3$ scaling, the LSI_c has to be adjusted to a negative value, except if adding scale inhibitor (Section 3.3.3) or preventive cleaning (Section 3.3.7) is applied.

The conditions for $CaCO_3$ scale control are:

$LSI_c < 0$ when no antiscalant is added

$LSI_c \leq 1.0$ when 20 mg/l sodium hexametaphosphate is in the concentrate stream

$LSI_c > 1$ is possible with approved polymeric organic scale inhibitors. For the maximum LSI_c and required dosages, please refer to the scale inhibitor manufacturer's literature.

If the LSI_c is not within above conditions, adjustments can be made by one of the following means. A new LSI_c can then be calculated.

a. The recovery (Y) can be lowered and the LSI_c can be calculated as above by substituting a new value for the recovery.

b. Decreasing the calcium concentration in the feed solution by means of sodium cycle ion exchange. This will increase the pCa and will therefore decrease the LSI_c. Softening will not change the alkalinity or pH of the feed solution and the slight change in TDS_f may be considered negligible. After softening, the LSI_c can be calculated as above using the lower value for calcium concentration.

c. Adding acid (HCl, CO_2, H_2SO_4, etc.) to the feed solution changes the Alk_f, C_f and pH. The slight change in TDS_f can usually be neglected. Acid addition will decrease the LSI_c; however, since many variables change with acidification, trial and error computations are required to determine the amount of acid needed to obtain the desired LSI_c. The number of trial and error computations required to determine the amount of acid needed can be reduced greatly by using the pH_s calculated in Eq 9. Since pH_c will usually be 0.5 units higher than the pH_f, the first computation can be made with an acidified feed solution which is 0.5 unit lower than the pH_s.

c1. For an assumed pH (pH_{acid}), obtained from addition of acid to the feed solution, obtain the ratio of Alk_{acid}/C_{acid} from Fig. 1. From this ratio, Alk_f, and C_f calculate the milligrams per liter of acid used (x). For example, for H_2SO_4 addition (100%):

$$\frac{Alk_{acid}}{C_{acid}} = \frac{Alk_f - 1.02x}{C_f + 0.90x} \qquad (11)$$

c2. Calculate the total alkalinity of the acidified feedwater (Alk_{acid}) and the CO_2 content in the acidified feedwater (C_{acid}) as follows:

$$Alk_{acid} = Alk_f - 1.02x \qquad (12)$$

$$C_{acid} = C_f + 0.90x \qquad (13)$$

c3. Using Alk_{acid} and C_{acid} for the new pH, calculate the LSI_c.

c4. If HCl (100%) is used for acidification, the Eq 6 is:

$$\frac{Alk_{acid}}{C_{acid}} = \frac{Alk_f - 1.37y}{C_f + 1.21y} \qquad (14)$$

where: y = HCl (100%), mg/l.

Reverse Osmosis in Operation
Once a reverse osmosis system is operating, the Langelier Saturation Index can be directly calculated from the analysis of Alk_c, Ca_c, TDS_c and pH_c of the concentrate stream and compared with the projected LSI_c.

Use of Computers
The LSI_c and the acid dosage required to adjust a certain LSI_c can be determined using a personal computer and the FILMTEC® Reverse Osmosis System Analysis (ROSA) computer program. Please refer to the Computer Program Manual.

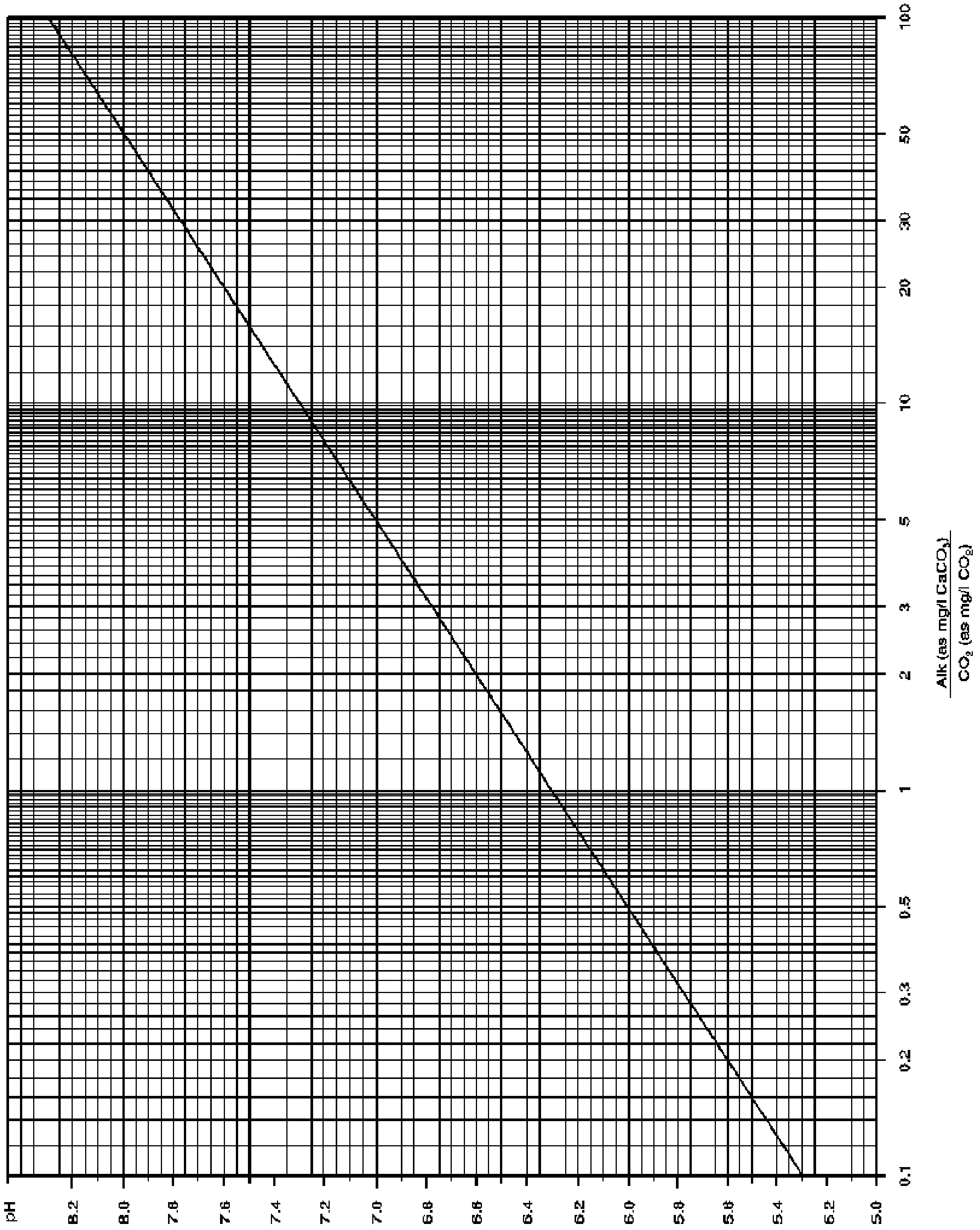
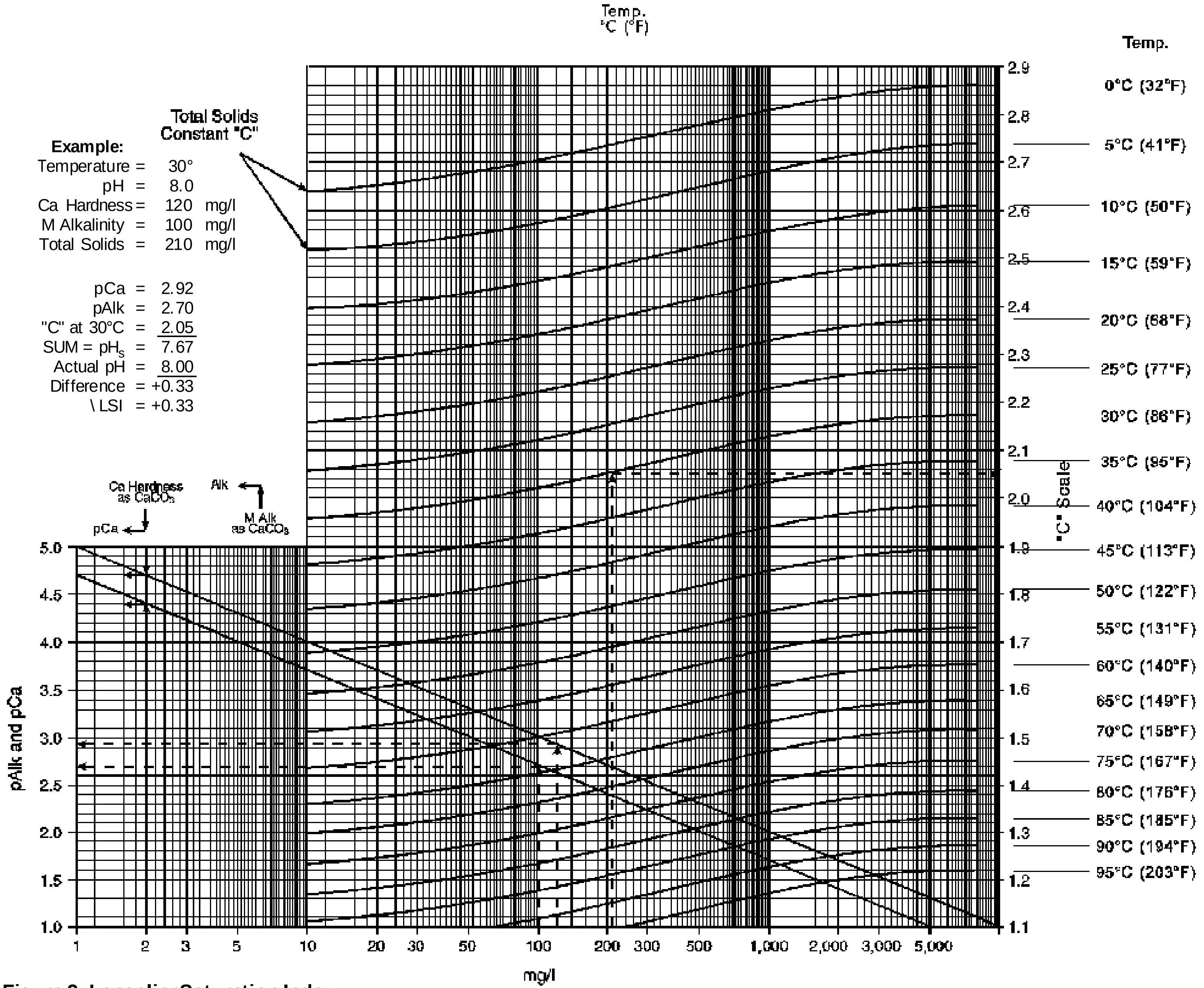


Figure 1: pH versus Methyl Orange Alkalinity / Free CO_2



Example:

Temperature = 30°
pH = 8.0
Ca Hardness = 120 mg/l
M Alkalinity = 100 mg/l
Total Solids = 210 mg/l

pCa = 2.92
pAlk = 2.70
"C" at 30°C = 2.05
SUM = pH_s = 7.67
Actual pH = 8.00
Difference = +0.33
\ LSI = +0.33

Figure 2: Langelier Saturation Index

3.4.2.2 Sea Water

For high salinity brackish waters with TDS > 10,000 mg/l in the concentrate stream and for sea waters, the Stiff & Davis Stability Index (S&DSI) is used to express the scaling potential for calcium carbonate. The data needed to calculate the S&DSI of the concentrate stream are the same as those needed to calculate the LSI (see previous section). Additionally, the molal concentrations of all ions in the feed solution are required, at least of all major ions, that is, Ca^{++}, Mg^{++}, Na^{+}, K^{+}, HCO_3^{-}, SO_4^{--} and Cl^{-}.

Calculation

a. Calculate the calcium concentration in the concentrate stream, Ca_c, as $CaCO_3$ in mg/l:

$$Ca_c = Ca_f \times \frac{1}{1\text{-}Y} \qquad (6)$$

b. Calculate the alkalinity in the concentrate stream, Alk_c, as $CaCO_3$ in mg/l:

$$Alk_c = Alk_f \times \frac{1}{1\text{-}Y} \qquad (8)$$

c. Calculate the ionic strength of the feed stream (I_f):

$$\frac{1}{2}$$

d. Calculate the ionic strength of the concentrate stream (I_c):

$$I_c = I_f \times \frac{1}{1\text{-}Y} \qquad (5)$$

e. From Figure 3, obtain pCa as a function of Ca_c and pAlk as a function of Alk_c. From Figure 4, obtain the constant "K" as a function of concentrate ionic strength and feed temperature.

f. Calculate the pH at which the concentrate stream is saturated with $CaCO_3$ (pH_s) as follows:
$pH_s = pCa + pAlk + \text{“K”}$

g. Calculate the free carbon dioxide content (C) in the concentrate stream by assuming that the CO_2 concentration in the concentrate is equal to the CO_2 concentration in the feed: $C_c = C_f$. The concentration of free carbon dioxide in the feed solution is obtained from Fig. 1 as a function of the alkalinity and the pH of the feed solution.

h. Calculate the pH of the concentrate stream (pH_c) using the ratio of alkalinity (from Eq. 8) to free CO_2 in the concentrate (from g), Fig. 1.

i. Calculate the Stiff and Davis Stability Index of the concentrate ($S\&DSI_c$) as follows:
$S\&DSI_c = pH_c - pH_s$

Adjustments of $S\&DSI_c$

The $S\&DSI_c$ in the concentrate stream would be positive with most natural high salinity waters. In order to prevent $CaCO_3$ precipitation and scaling, the $S\&DSI_c$ has to be adjusted to a negative value. The $S\&DSI_c$ may be positive however, if $CaCO_3$ precipitation is prevented by the dosage of an approved scale inhibitor (see Section 4.3.3). For the maximum allowed $S\&DSI_c$ and the required dosage, please refer to the scale inhibitor manufacturer's literature.

If the $S\&DSI_c$ is unacceptable based on the above recommendation, adjustments can be made by one of the following means. A new $S\&DSI_c$ can then be calculated.

a. The recovery can be lowered and the $S\&DSI_c$ can be calculated as above by substituting a new value for the recovery.
b. Decreasing the calcium and alkalinity concentrations in the feed solution by means of lime or lime-soda ash softening will increase the pCa and pAlk and will therefore decrease the pH_s.
c. Addition of acid (HCl, CO_2, H_2SO_4, etc.) to the feed solution either with or without lime or lime-soda ash softening changes the Alk_f, C_f and pH. The slight change in I_f can usually be ignored. Acid addition will decrease the $S\&DSI_c$; however, since many variables change with acidification, trial and error computations are required to determine the amount of acid needed to obtain the desired $S\&DSI_c$.
These computations have been described already in the previous section (3.4.2.1 Brackish Water). For sea water systems, a dosage of typically 10 mg/l sulfuric acid is required to achieve a pH_f of about 7 and a negative S&DSI in the concentrate.

Reverse Osmosis in Operation

Once a reverse osmosis system is operating, the $S\&DSI_c$ can be directly calculated from the analysis of Alk_c, Ca_c, pH_c and I_c of the concentrate stream and compared with the projected $S\&DSI_c$.

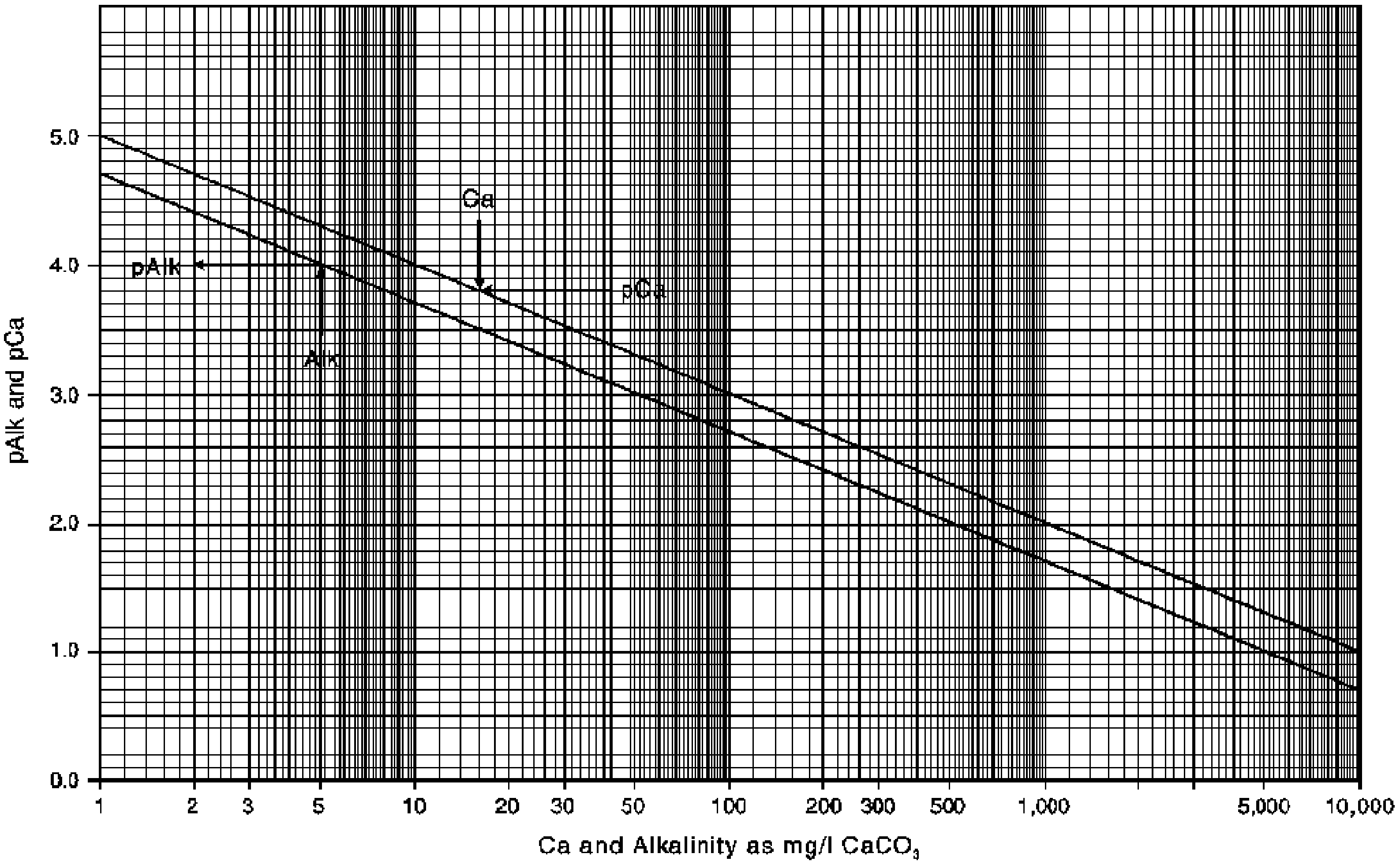


Figure 3: Conversion of Calcium and Alkalinity to pCa and pAlk

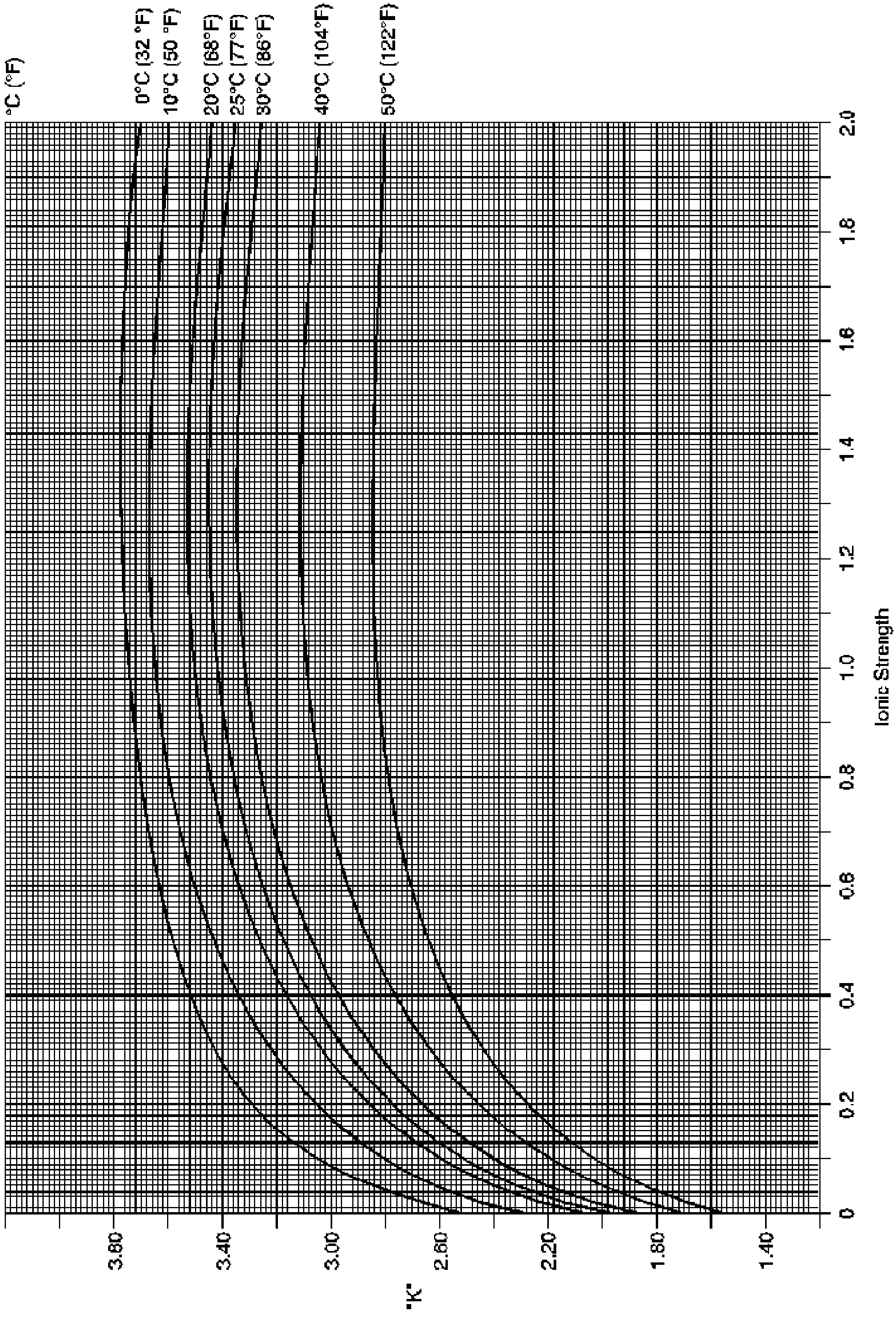


Figure 4: "K" versus Ionic Strength and Temperature

3.4.3
Calcium Sulfate Scale Prevention

For the determination of the calcium sulfate scaling potential, a complete feed water analysis is required.

Calculation

a. Calculate the ionic strength of the concentrate stream (I_c) following the procedure described in Section 4.4.1:

$$I_c = I_f \times \frac{1}{1-Y} \qquad (5)$$

b. Calculate the ion product (IP_c) for $CaSO_4$ in the concentrate stream:

$$IP_c = [({}^{m}Ca^{++})_f \times \frac{1}{1\text{-}Y}] \times [({}^{m}SO_4^{--})_f \times \frac{1}{1\text{-}Y}]$$

where:
$({}^{m}Ca^{++})_f$ = M Ca^{++} in feed, mol/l
$({}^{m}SO_4^{--})_f$ = M SO_4^{--} in feed, mol/l

c. Compare IP_c for $CaSO_4$ with the solubility product (K_{sp}) of $CaSO_4$ at the ionic strength of the concentrate stream, Figure 5. If $IP_c \geq K_{sp}$, $CaSO_4$ scaling can occur, and adjustment is required. For a safe and conservative pretreatment design, adjustment should be made if $IP_c > 0.8\ K_{sp}$.

Calculation Example (continued from page 4.4 page 1):

a. $I_c = 0.178$

b. $IP_c = (5 \times 10^{-3} \times 4) \times (5 \times 10^{-3} \times 4)$
$= 4 \times 10^{-4}$

c. $K_{sp} = 4.4 \times 10^{-4}$ (from Figure 5)

$IP_c = 0.9\ K_{sp}$, therefore adjustments are required.

Adjustments for $CaSO_4$ Scale Control

a. If the IP_c for $CaSO_4$ is less than $0.8\ K_{sp}$, a higher recovery can be used with respect to $CaSO_4$ scaling. Reiteration of the calculations at higher recovery can be used to determine the maximum conversion with respect to $CaSO_4$ scaling.

b. If the IP_c for $CaSO_4$ is greater than $0.8\ K_{sp}$, a lower recovery must be used to prevent scaling. Reiteration of the calculations at lower recovery can be used to determine the allowable recovery with respect to $CaSO_4$ scaling.

c. If the maximum allowable recovery is lower than desired, strong acid cation exchange resin softening (Section 3.3.4) or weak acid cation exchange resin dealkalization (Section 3.3.5) can be used to remove all or part of the Ca^{++}. This will permit higher recovery of the reverse osmosis system with respect to $CaSO_4$ scaling.

d. Lime softening with lime or lime plus soda ash (see Section 3.3.6) will decrease the Ca^{++} concentration and thus permit higher recovery with respect to scaling by $CaSO_4$.

e. Addition of a scale inhibitor to the feed stream permits operation of the reverse osmosis system above the K_{sp} value. When an approved and adequate scale inhibitor is added according to the scale inhibitor manufacturer's instructions, the IP_c for $CaSO_4$ must be less than $2.0\ K_{sp}$. When sodium hexametaphosphate is used as a scale inhibitor, the limitation is:
$IP_c \leq 1.0 \times 10^{-3}$ and
$IP_c \leq 1.5\ K_{sp}$.

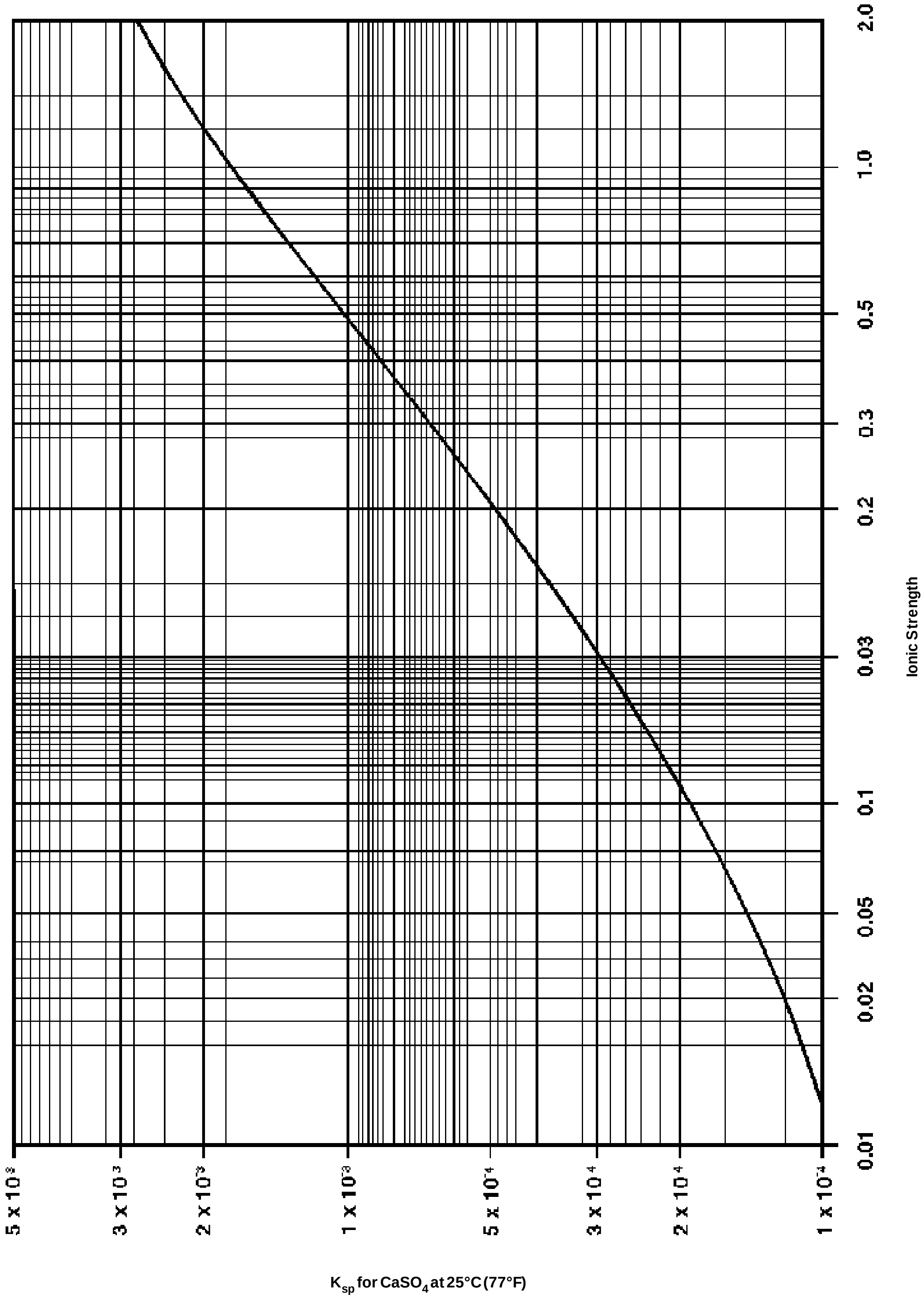


Figure 5: K_{sp} for $CaSO_4$ versus Ionic Strength [20)]

3.4.4
Barium Sulfate Scale Prevention

Barium sulfate is the most insoluble of all alkaline-earth sulfates. When present in water, it may lead to massive precipitations, possibly acting as a catalyst for calcium sulfate and strontium sulfate scaling.

In most natural waters, barium is present at a level that would cause barium sulfate precipitation in the concentrate stream. The critical feed concentration of barium may be as low as < 15 µg/l in sea waters, < 5 µg/l in brackish waters or even < 2 µg/l if sulfuric acid is dosed to brackish waters.

Calculation
Prediction of $BaSO_4$ scaling potential is performed in the same way as the previously described procedure for $CaSO_4$.

a. Calculate the ionic strength of the concentrate stream (I_c) following the procedure described in Section 3.4.1:

$$I_c = I_f \times \frac{1}{1-Y} \qquad (5)$$

b. Calculate the ion product (IP_c) for $BaSO_4$ in the concentrate stream:

$$IP_c = [({}^mBa^{++})_f \times \frac{1}{1-Y}] \times [({}^mSO_4^{--})_f \times \frac{1}{1-Y}]$$

where:
$({}^mBa^{++})_f$ = M Ba^{++} in feed, mol/l
$({}^mSO_4^{--})_f$ = M SO_4^{--} in feed, mol/l

c. Compare IP_c for $BaSO_4$ with the solubility product (K_{sp}) of $BaSO_4$ at the ionic strength of the concentrate stream, Figure 6. If $IP_c \geq K_{sp}$, $BaSO_4$ scaling can occur, and adjustment is required.

Adjustments for $BaSO_4$ Scale Control
The adjustments discussed in Section 3.4.3 for $CaSO_4$ scale control apply as well for $BaSO_4$ scale control.
When an adequate scale inhibitor is used, the limitation is:

$IP_c \leq 50\ K_{sp}$

3.4.5
Strontium Sulfate Scale Prevention

Calculation
Prediction of $SrSO_4$ scaling potential is performed in the same way as the previously described procedure for $CaSO_4$:

a. Calculate the ionic strength of the concentrate stream (I_c) following the procedure described in Section 3.4.1:

$$I_c = I_f \times \frac{1}{1-Y} \qquad (5)$$

b. Calculate the ion product (IP_c) for $SrSO_4$ in the concentrate stream:

$$IP_c = [({}^mSr^{++})_f \times \frac{1}{1-Y}] \times [({}^mSO_4^{--})_f \times \frac{1}{1-Y}]$$

where:
$({}^mSr^{++})_f$ = M Sr^{++} in feed, mol/l
$({}^mSO_4^{--})_f$ = M SO_4^{--} in feed, mol/l

c. Compare IP_c for $SrSO_4$ with the solubility product (K_{sp}) of $SrSO_4$ at the ionic strength of the concentrate stream, Figure 7. If $IP_c \geq 0.8\ K_{sp}$, $SrSO_4$ scaling can occur, and adjustment is required.

Adjustments for $SrSO_4$ Scale Control
The adjustments discussed in Section 3.4.3 for $CaSO_4$ scale control apply for $SrSO_4$ scale control as well.

When an adequate scale inhibitor is used, the limitation is:

$IP_c \leq 50\ K_{sp}$

3.4.6
Calcium Fluoride Scale Prevention

Fluoride levels in the feed water of as low as 0.1 mg/l can create a scaling potential, if the calcium concentration is high. The calculation of the scaling potential is analogous to the procedure described in Section 3.4.3 for $CaSO_4$.

Calculation

a. Calculate the ionic strength of the concentrate stream (I_c) following the procedure described in Section 3.4.1:

$$I_c = I_f \times \frac{1}{1-Y} \qquad (5)$$

b. Calculate the ion product (IP_c) for CaF_2 in the concentrate stream:

$$IP_c = [({}^mCa^{++})_f \times \frac{1}{1-Y}] \times [({}^mF^{-})_f \times \frac{1}{1-Y}]^2$$

where:
$({}^mCa^{++})_f$ = M Ca^{++} in feed, mol/l
$({}^mF^{-})_f$ = M F^{-} in feed, mol/l

c. Compare IP_c for CaF_2 with the solubility product (K_{sp}) of CaF_2 at the ionic strength of the concentrate stream, Figure 8. If $IP_c \geq K_{sp}$, CaF_2 scaling can occur, and adjustment is required.

Adjustments for CaF_2 Scale Control
The adjustments discussed in Section 3.4.3 for $CaSO_4$ scale control apply as well for CaF_2 scale control.

When an adequate scale inhibitor is used, the limitation is:

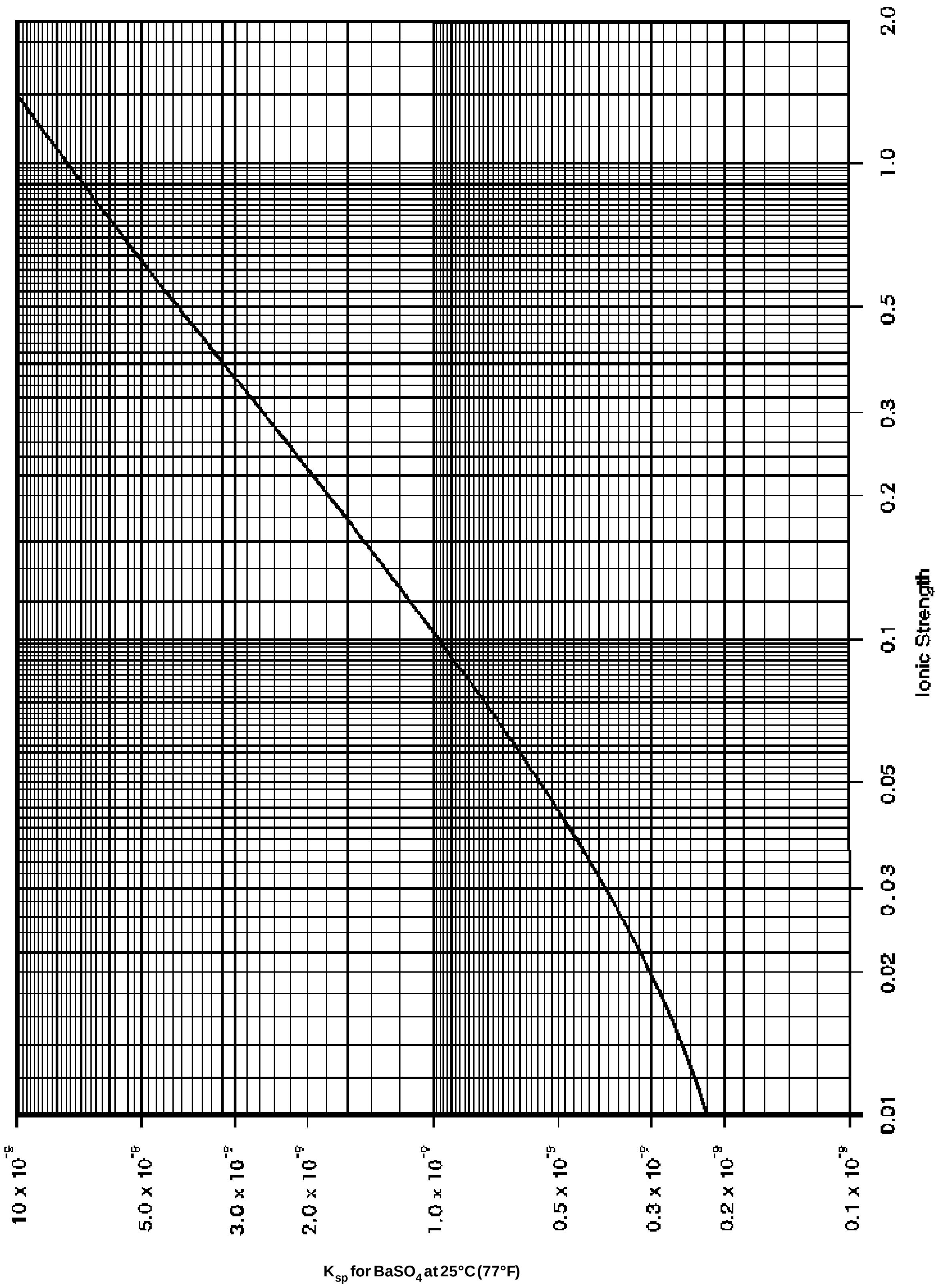


Figure 6: K_{sp} for $BaSO_4$ versus Ionic Strength 21)

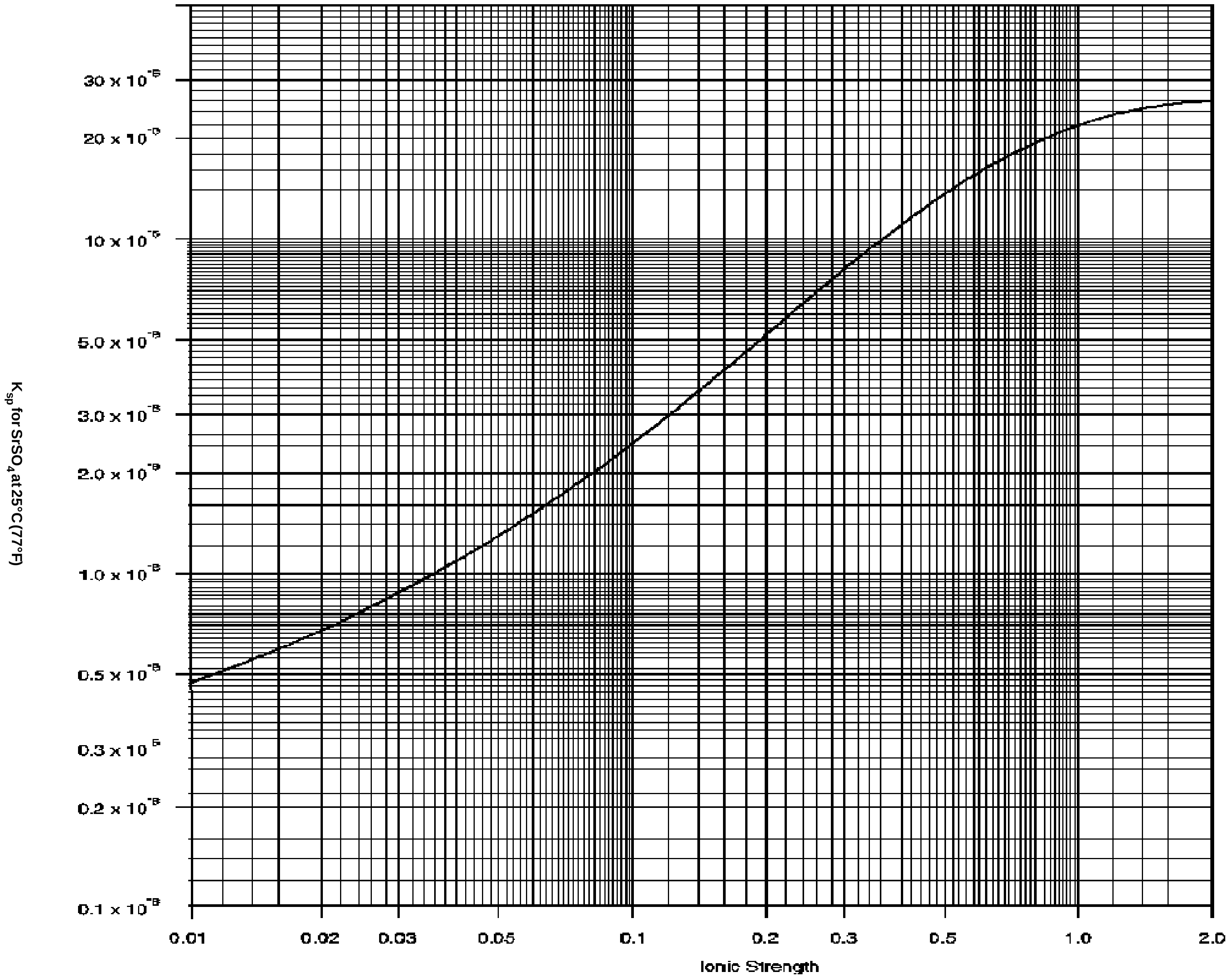


Figure 7: K_{sp} for $SrSO_4$ versus Ionic Strength [21)]

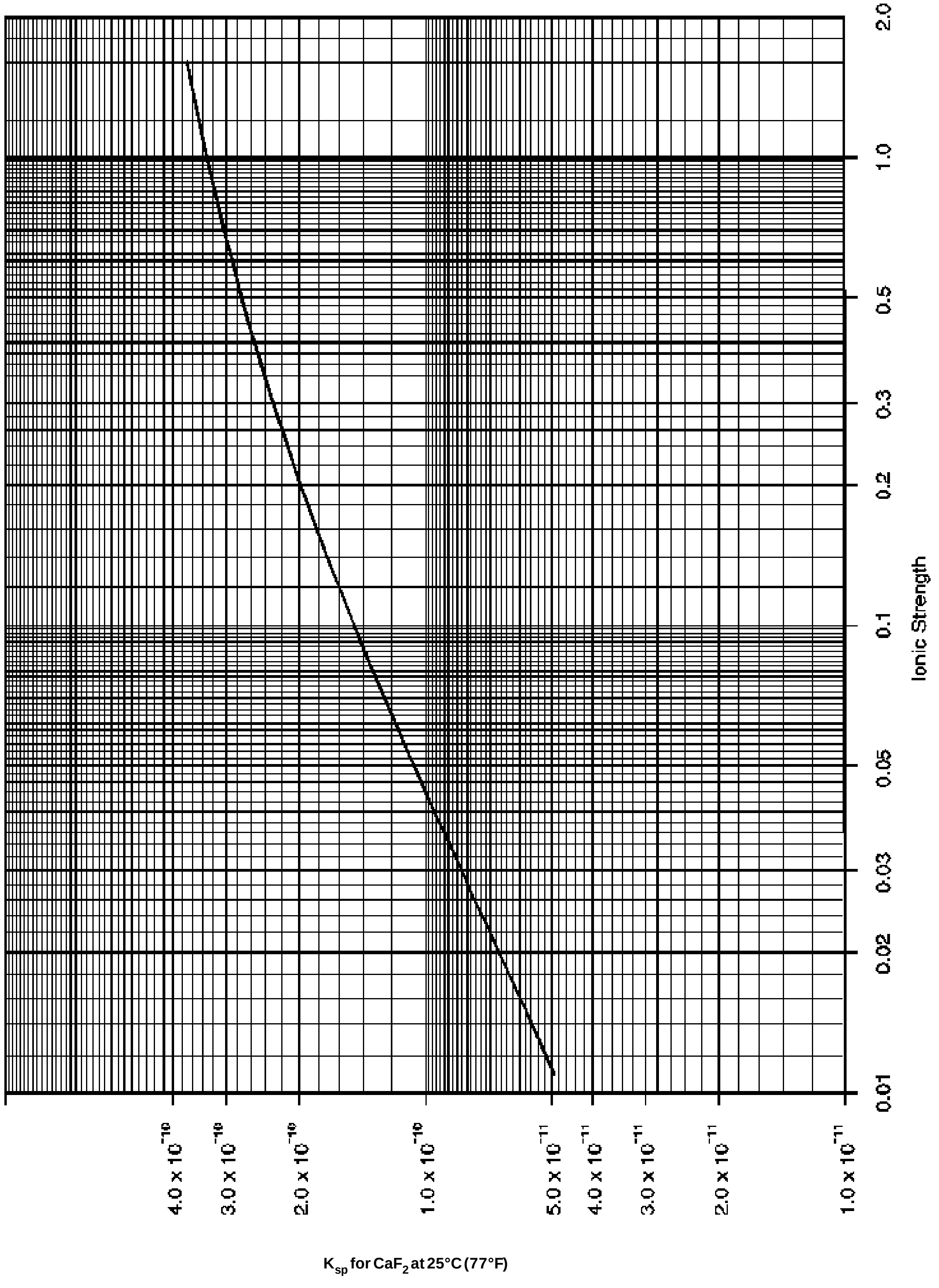


Figure 8: K_{sp} for CaF_2 versus Ionic Strength

$IP_c \leq 100\ K_{sp}$

3.4.7 Silica Scale Prevention

Dissolved silica (SiO_2) is naturally present in most feedwaters in the range of 1-100 mg/l. Supersaturated, SiO_2 can polymerize to form insoluble colloidal silica or silica gel, which can cause membrane scaling. The maximum allowable SiO_2 concentration in the concentrate stream is based on the solubility of SiO_2.

The scaling potential for the concentrate stream will be quite different from that of the feed solution, because of the increase in the concentration of SiO_2, and the change in pH. It can be calculated from the feed water analysis and the reverse osmosis operating parameters.

The presence of certain metals, for example, Al^{3+}, may significantly alter the solubility of SiO_2 via formation of insoluble metal silicates. The occurrence of silica scaling is mostly correlated with the occurrence of aluminium or iron. Therefore, if a silica scaling potential exists, the absence of aluminium and iron must be ensured. We recommend 1 µm cartridge filtration and preventive acid cleanings in this case.

The calculation of the silica scaling potential requires the following data of the feed solution (after acid addition, if acid is used for control of calcium carbonate):

- SiO_2 concentration
- Temperature
- pH
- Total alkalinity

Calculation

a. The SiO_2 concentration in the concentrate stream is calculated from the SiO_2 concentration in the feed solution and the recovery of the reverse osmosis system:

$$SiO_{2c} = SiO_{2f} \times \frac{1}{1-Y}$$

where:

SiO_{2c} = silica concentration in concentrate as SiO_2, mg/l

SiO_{2f} = silica concentration in feed as SiO_2, mg/l

Y = recovery of the reverse osmosis system, expressed as a decimal

b. Calculate the pH of the concentrate stream from the pH of the feed stream using the procedure given in Section 3.4.2, Calcium Carbonate Scale Prevention.

c. From Figure 9, obtain the solubility of SiO_2 as a function of temperature (SiO_2 temp.). **Note:** Temperature of the concentrate is assumed equal to temperature of feed solution. If the temperature of the water is known to vary, use the minimum temperature for calculations.

d. From Figure 10, obtain the pH correction factor for the concentrate pH calculated in b.

e. Calculate the solubility of SiO_2 corrected for pH ($SiO_{2corr.}$) by multiplying the solubility of SiO_2 obtained in c. by the pH correction factor obtained in d.

f. Compare the silica concentration in the concentrate (SiO_{2c}) obtained in a. with the silica solubility ($SiO_{2corr.}$) obtained in e. Once a reverse osmosis system is operating, the scaling potential of SiO_2 can be directly calculated from the analysis of the concentrate stream and compared with the projected scaling potential calculated above. If SiO_{2c} is greater than $SiO_{2corr.}$, silica scaling can occur and adjustment is required.

Adjustments for Scale Control

a. If SiO_{2c} is less than $SiO_{2corr.}$, a higher recovery can be used with respect to scaling by silica. Reiteration of the calculations at higher recovery can be used to determine the maximum conversion with respect to scaling by silica.

b. If SiO_{2c} is greater than $SiO_{2corr.}$, a lower recovery must be used to prevent scaling. Reiteration of the calculations can be used to determine the allowable recovery with respect to scaling by silica.

c. If the maximum allowable recovery is lower than desired, lime plus soda ash softening employing either magnesium oxide or sodium aluminate can be used in the pretreatment system to decrease the SiO_2 concentration in the feed stream (see Section 3.3.6) and thus permit higher conversion with respect to scaling by silica. It is important that the softening process be performed properly in order to prevent formation of insoluble metal silicates in the reverse osmosis system.

d. Since the solubility of silica increases below a pH of about 7.0 and above a pH of about 7.8, pH adjustment with either acid or base can permit a higher recovery with respect to silica scaling. However, for the high pH, $CaCO_3$ scaling must be prevented.

e. The maximum allowable recovery with respect to silica scaling can be increased significantly by increasing the water temperature using a heat exchanger. The maximum temperature permitted

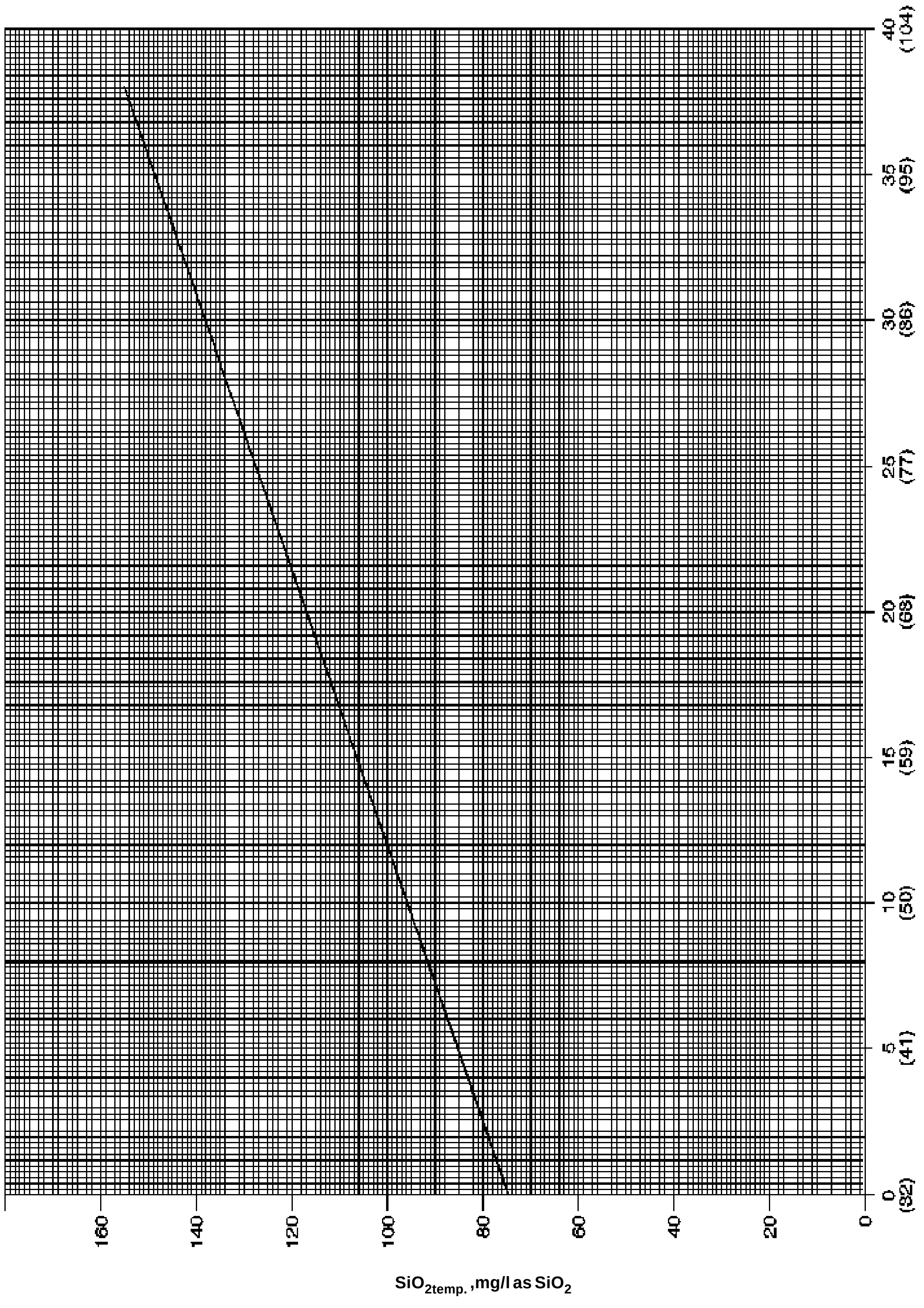


Figure 9: Solubility of SiO_2 versus Temperature[19)]

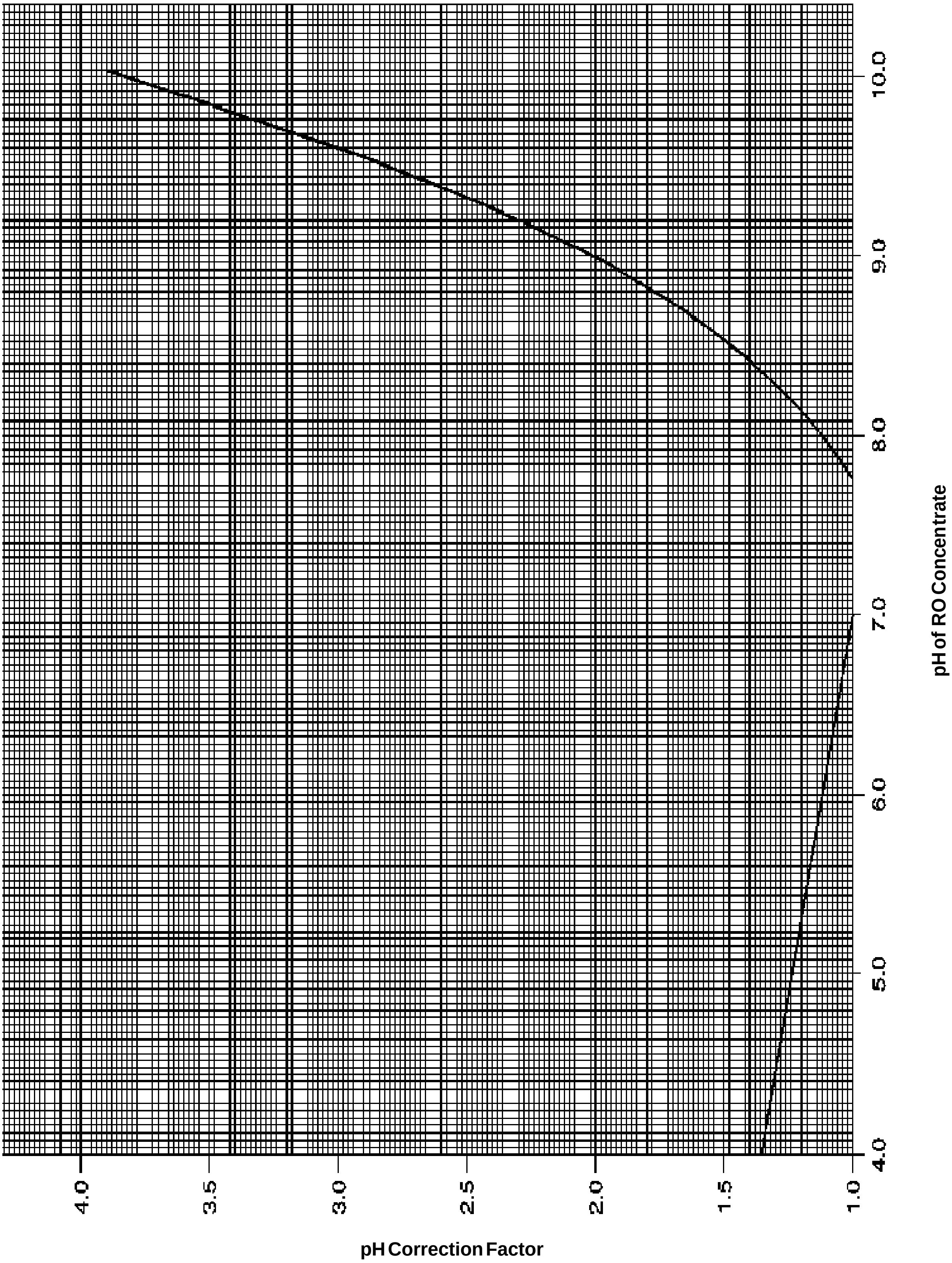


Figure 10: **SiO$_2$ pH Correction Factor** 22)

for continuous use is 45°C.

3.5 Colloidal Fouling Prevention

3.5.1 Introduction

Colloidal fouling of reverse osmosis elements can seriously impair performance by lowering productivity and sometimes salt rejection. An early sign of colloidal fouling is often an increased pressure differential across the system.

The source of silt or colloids in reverse osmosis feed waters is varied and often includes bacteria, clay, colloidal silica, and iron corrosion products. Pretreatment chemicals used in a clarifier such as alum, ferric chloride, or cationic polyelectrolytes can also cause colloidal fouling if not removed in the clarifier or through proper media filtration. In addition, cationic polymers may coprecipitate with negatively charged antiscalants and foul the membrane.

The best available technology for determining the colloidal fouling potential of reverse osmosis feed water is the measurement of the Silt Density Index (SDI), sometimes referred to as the Fouling Index (FI). This is an important measurement to be carried out prior to designing an RO pretreatment system and on a regular basis during RO operation (three times a day is a recommended frequency for surface waters).

The Standard Test Method has been described in ASTM test D 4189-82.

Equipment
(Available from Millipore Corporation)

- 47 mm diameter membrane filter support
- 47 mm diameter membrane filters (0.45 µm pore size)
- 1 to 5 bar (10-70 PSI) manometer
- needle valve for pressure adjustment

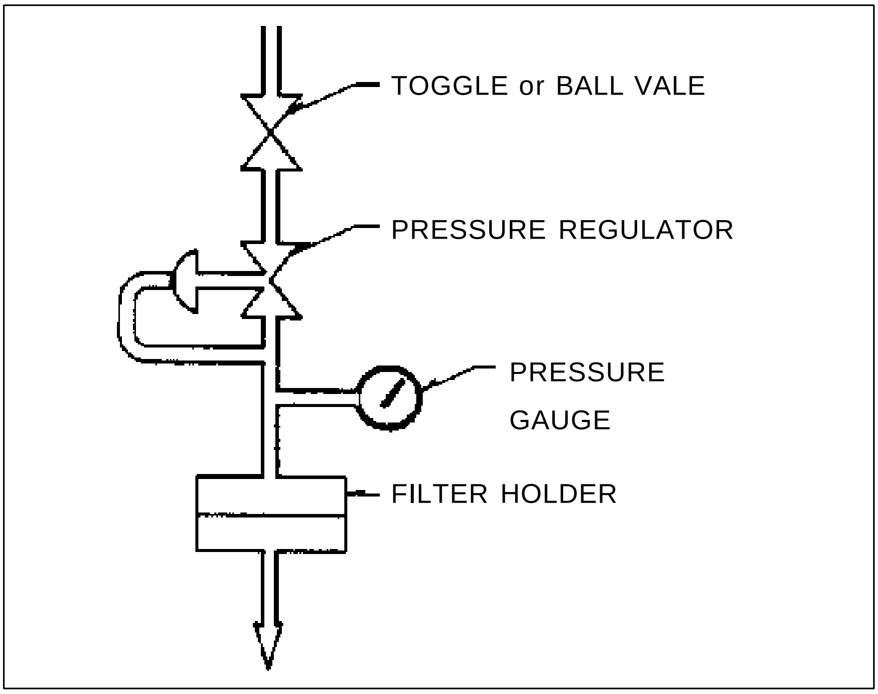


Figure 1: Apparatus for Measuring the Silt Density Index

Figure 1 shows the equipment needed to measure SDI.

Procedure

a. Place the membrane filter on its support, bleed water pressure on carefully, tighten the O-ring seal and fix the support vertically.

b. Adjust feed pressure to 2.1 bar (30 PSI) and measure initial time, t_O, necessary to filter 500 ml of sample water (feed pressure to be kept constant by continuous adjustment).

c. Keep filter in operation for 15 minutes under 2.1 bar (30 PSI) feed pressure.

d. After 15 minutes measure again time, t_1, necessary to filter 500 ml. Membrane filter should be kept for further analysis.

e. Calculation:

$$SDI = \left[1 - \frac{t_O}{t_1} \right] \times \frac{100}{15}$$

When t_1 is four times as long as t_0, the resulting SDI is 5. A water sample that totally blocks the membrane filter has an SDI value of 6.7.

The guideline is to maintain SDI at less than or equal to 5. A number of pretreatment technologies have proven effective in SDI reduction including media filtration (such as sand/anthracite), ultrafiltration, cross flow microfiltration. Polyelectrolyte addition ahead of filtration sometimes improves SDI reduction.

Methods to prevent colloidal fouling are outlined in the following chapters.

3.5.2
Media Filtration

The removal of suspended and colloidal particles by media filtration is based on their deposition on the surface of filter grains, while the water flows through a bed of these grains (filter media). The quality of the filtrate depends on the size, surface charge and geometry of both suspended solids and filter media, as well as on the water analysis and operational parameters. With a well designed and operated filter, a SDI<5 can usually be achieved.

The most common filter media in water treatment are sand and anthracite. The effective grain size for fine sand filter is in the range of 0.35 to 0.5 mm, and 0.7 to 0.8 mm for anthracite filter. In comparison to single sand filter media, dual filter media with anthracite over sand permit more penetration of the suspended matter into the filter bed, thus resulting in more efficient filtration and longer runs between cleaning.

The design depth of the filter media is normally about 0.8 m (31 inches) minimum. In the dual filter media, the filters are usually filled with 0.5 m (20 inches) of sand covered with 0.3 m (12 inches) of anthracite.

There are two types of filters employed, gravity and pressure filters. As the filter vessel for pressure filtration is designed for pressurization, a higher pressure drop can be applied for higher filter beds and/or smaller filter grains and/or higher filtration velocities.

The design filtration flow rates are usually 10-20 m/h, and the backwash rates are in the range of 40-50 m/h.

For feedwaters with a high fouling potential, flow rates of less than 10m/h and/or second pass media filtration is preferred.

The available pressure is usually about 5 m of head for gravity filters, and 2 bar (30 PSI) to more than 4 bar (60 PSI) for pressure filters.

During operation, influent water to be filtered enters at the top of the filter, percolates through the filter bed, and is drawn off through the collector system at the bottom. Periodically, when the differential pressure increase between the inlet and outlet of the filter is 0.3 to 0.6 bar (4 to 9 PSI) for the pressure filter, and about 1.4 m for the gravity filter, the filter is backwashed and rinsed to carry away the deposited matter. Backwash time is normally about 10 min.

Frequent shut-downs and start-ups should be avoided, because each filter velocity increase will release previously deposited particulate matter.

Design and operational details of media filtration are available in the literature [1) 2)].

3.5.3
Oxidation – Filtration

Some well waters, usually brackish waters, are in a reduced state. Typical for these waters is the absence of oxygen and the presence of divalent iron and manganese, sometimes also of hydrogen sulfide and ammonium.

If such a water has been chlorinated and then dechlorinated, or has taken up more than 5 mg/l of oxygen, Fe^{2+} is converted into Fe^{3+}, which forms insoluble colloidal hydroxide particles. The oxidation of iron and manganese is given by:

$$4\,Fe(HCO_3)_2 + O_2 + 2H_2O \rightarrow 4\,Fe(OH)_3 + 8\,CO_2$$

$$4\,Mn(HCO_3)_2 + O_2 + 2H_2O \rightarrow 4\,Mn(OH)_3 + 8\,CO_2$$

Iron fouling occurs more frequently than manganese fouling, since the oxidation of iron occurs at a much lower pH. Thus a fouling problem can be created even if the SDI is below 5, and the level of iron in the RO feed water is below 0.1 mg/l. Waters with low alkalinity usually have higher iron concentrations than waters with high alkalinity, because the Fe^{2+} concentration is usually limited by the solubility of $FeCO_3$.

One method of handling such waters is to prevent the exposure to air or to any oxidizing agent, e.g. chlorine, through the whole RO process. A low pH is favorable to retard Fe^{2+} oxidation. At pH < 6 and oxygen < 0.5 mg/l, the maximum permissible Fe^{2+} concentration is 4 mg/l.

The other way is to deliberately oxidize iron and manganese by air, Cl_2 or $KMnO_4$. The formed hydroxides can then be removed by media filtration. Colloidal sulfur as formed from hydrogen sulfide however, may be difficult to remove. Oxidation and filtration can be accomplished in one step by using a filter media with the ability to oxidize Fe^{2+} by electron transfer.

Greensand is such a granular medium, which is a green (when dry) mineral glauconite. It can be regenerated with $KMnO_4$ when its oxidizing capability is exhausted. After the regeneration, the residual $KMnO_4$ has to be thoroughly rinsed out in order to avoid an oxidation damage of the membranes. This technique is used when < 2 mg/l Fe^{2+} is present in the raw water. For higher Fe^{2+} concentrations, $KMnO_4$ can be continuously dosed into the inlet stream of the filter. In this case however, measures have to be taken to assure that no permanganate can reach the membranes, for example by installation of a carbon filter (see Section 3.6.4, Dechlorination).

Birm filtration has also been used effectively for Fe^{2+} removal from RO feed water. Since with birm a pH increase and consequently a shift in the LSI value might occur, care should be taken to avoid $CaCO_3$ precipitation in the filter and in the RO system.

3.5.4
In-Line Filtration

The efficiency of media filtration to reduce the SDI value can be markedly improved if the colloids in the raw water are coagulated and/or flocculated prior to filtration. In-line filtration can be applied to raw waters with an SDI only slightly above 5.

The method, also named in-line coagulation or in-line coagulation-flocculation, is described in ASTM Standard D 4188. A coagulant is injected into the raw water stream, effectively mixed, and the formed microflocs are immediately removed by media filtration.

Ferric sulfate and ferric chloride are used to destabilize the negative surface charge of the colloids and to entrap them into the freshly formed ferric hydroxide microflocs. Aluminium coagulants are also effective, but not recommended because of possible fouling problems with residual aluminium.

Rapid dispersion and mixing of the coagulant is extremely important. An in-line static mixer or injection on the suction side of a booster pump is recommended. The optimum dosage is usually in the range of 10 to 30 mg/l, but should be determined case by case.

To strengthen the hydroxide microflocs and thereby improving their filterability, and/or to bridge the colloidal particles together, flocculants can be used in combination with coagulants or alone. Flocculants are soluble high molecular mass organic compounds, e.g. linear polyacrylamides. Through different active groups, they may be positively charged (cationic), negatively charged (anionic), or close to neutral (non-ionic).

Coagulants and flocculants may interfere with an RO membrane directly or indirectly. Indirect interference occurs when the compound forms a precipitate which is deposited on the membrane. For example, channelling of the media filter may enable flocs to pass through and deposit on the membrane. A precipitate can also be formed when concentrating the treated feedwater, such as when aluminium or ferric coagulants are added without subsequently lowering pH to avoid supersaturation in the RO stage. Furthermore, reaction with a compound added after the media filter can cause a precipitate to form. This is most noticeable with antiscalants. Nearly all antiscalants are negatively charged and will react with cationic coagulants or flocculants present in the water. Several RO plants have been heavily fouled by a gel formed by reaction between cationic polyelectrolytes and antiscalants.

Direct interference occurs when the compound itself affects the membrane resulting in a flux loss. The ionic strength of the water may have an effect on the interference of the coagulant or flocculant with the membrane. If so, the result at brackish water conditions could be different from that at sea water conditions. To minimise the risk of direct or indirect interference with the RO membrane, anionic or nonionic flocculants are preferred rather than cationic ones. Overdosing must be avoided.

3.5.5
Coagulation – Flocculation

For raw waters containing high concentrations of suspended matter resulting in a high SDI, the classic coagulation – flocculation process is preferred. The hydroxide flocs are allowed to grow and to settle in specifically designed reaction chambers. The hydroxide sludge is removed, and the supernatant water is further treated by media filtration.

For the coagulation – flocculation process, either a solids-contact type clarifier (see also Section 3.3.6) or a compact coagulation – flocculation reactor may be used. For details, please refer to the general water treatment textbooks [1)] [2)].

3.5.6
Crossflow Microfiltration/Ultrafiltration

Crossflow filtration through a microfiltration (MF) or ultrafiltration (UF) membrane removes virtually all suspended matter and, in the case of ultrafiltration, also dissolved organic compounds depending on their molecular mass and on the molecular mass cutoff of the membrane. Hence, an SDI < 1 can be achieved with a well-designed and properly maintained microfiltration or ultrafiltration system. The fouling problem, now transferred from the RO membrane to the MF or UF membrane, has to be handled by this system. At the same time, a high MF/UF system recovery and a high specific permeate flow is requested for economic reasons. These objectives are usually achieved by periodic cleanings, either a forward flush or preferably a backflush. If a chlorine resistant membrane material is used, e.g. polysulfone or a ceramic membrane, chlorine can be added to the wash water in order to prevent biological fouling.

A review on microfiltration and ultrafiltration processes is given by Porter 5).

3.5.7
Cartridge Microfiltration

A cartridge filter with a pore size of less than 10 µm is the minimum pretreatment required for every RO system. It is a safety device to protect the membranes and the high pressure pump from suspended particles. Usually it is the last step of a pretreatment sequence. We recommend to use a pore size of 5 µm or less. The better the prefiltration is, the less cleaning of the RO membranes is required. When the silica concentration in the concentrate stream exceeds the theoretical solubility (see Section 3.4.7), cartridge filtration with 1 µm pore size is recommended in order to minimise the interaction with iron and aluminium colloids.
The filter should be sized on a flow rate according to the manufacturer's recommendation, and replaced before the pressure drop has increased to the permitted limit, but latest after 3 months. Backflushable filters are not recommended because of their lower efficiency and higher biofouling risk.

The cartridge filter should be made of a synthetic nondegradable material; e.g. nylon or polypropylene and equipped with a pressure gauge to indicate the differential pressure drop and thereby indicating the extent of its fouling. Regular inspections of used cartridges provide useful information regarding fouling risks and cleaning requirements.

If the differential pressure across the filter increases rapidly, it is an indication of possible problems in the raw water supply or in the pretreatment process. The filter provides some degree of short-term protection for the membranes while corrective action is taking place.

Replacing cartridge filters more often than every 1 to 3 months usually indicates a problem with the pretreatment. However, the cartridge filter is not meant to be a major component for the removal of high amounts of filterable solids. This would not only be an inefficient use of rather expensive filters, but would probably lead to premature failure of the membrane system due to the high probability that some of the unwanted material will break through. It may be considered however, to use upstream a second cartridge with larger pore size.

3.5.8
Other Methods

Other methods to prevent colloidal fouling than those described in the previous chapters also exist.
Lime softening has already been described as a method for silica removal (Section 3.3.6). Removal of iron and colloidal matter are further benefits.

Strong acid cation exchange resin softening does not only remove hardness, but also low concentrations of iron and aluminium that otherwise could foul the membranes. Softened water is also known to exhibit a lower fouling tendency than unsoftened water, because multivalent cations promote the adhesion of naturally occurring colloids, which are usually negatively charged.

Backflushable fine filters may be used upstream of the cartridge filters to protect these. They are however, no substitute for disposable cartridges.

3.5.9
Design and Operational Considerations

The prevention of colloidal fouling is not only a matter of the proper pretreatment technique, but also of the system design and operation. As an extreme example, a surface water could be pretreated by coagulation - flocculation and ultrafiltration. The RO system could then operate with a high permeate flux, and almost no cleaning would be required. If the same water however, would just be cartridge filtered, then the RO system would need much more membrane area, and the membranes would require frequent cleaning and maintenance. A poor pretreatment can be partially compensated by adding more membrane area and modifying the system (see Section 5), and by more frequent and/or harsh cleaning. On the other hand, improving the pretreatment means savings in membrane costs.

In order to minimize the pretreatment effort and/or improve the feed water quality, the best available raw water quality should be used. The intake of surface water, including sea water is of paramount importance. A contamination of the raw water with waste water effluent may cause serious problems in the RO plant. A deep well close to the shore or the river is preferred. If an open intake is required, it should be located well away from the shore and some meters below the water surface.

New wells often release suspended matter in the first days of operation. Care must be taken that wells are properly rinsed out.

Fouling by iron oxide is also a common problem. It can be avoided by selecting non-corrosive materials (see Section 4.13).

3.6 Biological Fouling Prevention

3.6.1 Introduction

All raw waters contain microorganisms: bacteria, algae, fungi, viruses and higher organisms. The typical size of bacteria is 1 to 3 µm. Microorganisms can be regarded as colloidal matter and removed by the pretreatment as discussed in Section 3.5. The difference from dead particles however, is their ability to reproduce and form a biofilm under favorable living conditions.

Microorganisms entering an RO system find a large membrane surface where the dissolved organic nutrients of the water are concentrated (due to concentration polarization): an ideal environment for the formation of a biofilm. Biological fouling of the membranes may seriously affect the performance of the RO system. The symptoms are an increase of the differential pressure from feed to concentrate, finally leading to telescoping and mechanical damage of the membrane elements (see Section 9.4.3, High Differential Pressure), and a membrane flux decline. Sometimes biofouling develops even on the permeate side, thus contaminating the product water.

A biofilm is difficult to remove, because it protects its microorganisms against the action of shear forces and disinfection chemicals. In addition, incompletely removed biofilms lead to a rapid regrowth.

Biological fouling prevention is therefore a major objective of the pretreatment process. The potential for biological fouling is higher with surface water than with well water. The assessment of this potential and the possible measures against biofouling are discussed in the following sections.

3.6.2 Assessment of the Biological Fouling Potential

3.6.2.1 Culture Techniques

The concentration of bacteria in water is directly related to the water's biological fouling potential. The Total Bacteria Count (TBC) is a quantitative expression of the total number of viable microorganisms in a water sample. It is determined according to ASTM F60 by filtering a measured quantity of water through a membrane filter. Subsequently, the organisms thus retained on the filter surface are cultured on the proper nutrient medium to develop colonies, which are then observed and counted at low power magnification.

The main advantage of this method is that it can be easily performed without expensive equipment. The test results however, are only available after up to seven days, and the counted colonies may represent as little as 1-10 % of the actual number of living microorganisms. Nevertheless, culture techniques are still valuable as indicators of the level and the trend of the biological fouling potential.

They can be applied to monitor the water quality from the intake through the subsequent treatment steps up to the concentrate stream and the permeate.

An increase of the TBC in the concentrate stream is an indication of a biofilm development on the membranes.

3.6.2.2 Direct Bacteria Count

Direct count techniques employ filtration of the water sample and counting the retained microorganisms on the filter plate directly under a microscope. To make the microorganisms visible, they are stained with acridine orange and viewed with an epi-illuminated fluorescent microscope,6).

Thus an accurate count of total microorganisms is obtained immediately. The types of microorganisms can be assessed and differentiated from debris particles. Living and dead cells, however, cannot be differentiated. This can be accomplished by the INT[1] technique, where the INT stain is reduced and accumulated only by living cells. Those can be readily distinguished from dead cells with phase microscopy,7).

Direct count methods should be preferred, because they are much faster and more accurate than culture techniques.

3.6.2.3 Biofilm Monitoring

The concentrations of microorganisms in raw water, in the feed stream and in the concentrate stream are important numbers to assess the biological fouling potential. However, other factors like the concentration and the kind of nutrients, and operating parameters can also determine the development of a biofilm. The formation of biofilms is being studied by several researchers, but not yet fully understood 8). The best method to detect biofouling in its early stage is to observe a test surface in the feed stream. The "Robbin sampler" is a simple device to expose small test surfaces to a water stream (details: see12)). These surface samples can be removed and examined for attached bacteria on a regular basis.

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[1] INT = 2-(p-iodophenyl)-3-(p-nitrophenyl)-5-phenyl tetrazolium chloride

A careful and periodic inspection of the cartridge filters and the interior of the feed and brine piping is also helpful. The presence of slime or odor is an indication for biofouling.

3.6.2.4 Other Methods

The bacterial growth potential of a given water sample can be assessed with the Werner method [9]. The sample is filter-sterilized, and an inorganic sterile nutrient salt solution is then added. Then, the sample is inoculated with a specific volume of a suspension of bacteria washed from the sterilizing filter. The growth rate of the bacteria can be quantified from a turbidity increase as measured by forward light scattering.

Other techniques measure the assimilable organic carbon or the biodegradable organic carbon. The various methods have been reviewed by Huck [10].

3.6.3 Chlorination

Chlorine (Cl_2) has been used for many years to treat municipal and industrial water and wastewaters as a disinfectant, because of its capacity to inactivate most pathogenic microorganisms quickly. The effectiveness of chlorine is dependent on the chlorine concentration, time of exposure and the pH of the water. Chlorine is used for the disinfection of potable water where a residual chlorine concentration near 0.5 mg/l is commonly used. In an industrial water treatment scheme, fouling of water intake lines, heat exchangers, sand filters, etc., may be prevented by maintaining a free residual chlorine concentration of 0.5-1.0 mg/l or higher, dependent on the organic content of the incoming water.

Chlorination as RO pretreatment is usually applied where biological fouling prevention is required, i.e. typically for surface waters. Chlorine is added at the intake, and a reaction time of 20-30 min. should be allowed. A free residual chlorine concentration of 0.5-1.0 mg/l should be maintained through the whole pretreatment line. Dechlorination upstream of the membranes is required however, to protect the membranes from oxidation (see Section 4.6.4, Dechlorination).

Chlorination chemistry

Chlorine is most commonly available as chlorine gas and the hypochlorites of sodium and calcium. In water, they hydrolyze instantaneously to hypochlorous acid:

$$Cl_2 + H_2O \rightarrow HOCl + HCl \qquad (1)$$

$$NaOCl + H_2O \rightarrow HOCl + NaOH \qquad (2)$$

$$Ca(OCl)_2 + 2\ H_2O \rightarrow 2\ HOCl + Ca(OH)_2 \qquad (3)$$

Hypochlorous acid dissociates in water to hydrogen ions and hypochlorite ions:

$$HOCl \leftrightarrow H^+ + OCl^- \qquad (4)$$

The sum of Cl_2, NaOCl, $Ca(OCl)_2$, HOCl and OCl^- is referred to as free available chlorine (FAC) or free residual chlorine (FRC), given as mg/l Cl_2. As discussed later, chloramines are formed from the reaction of chlorine with ammonia compounds present in the water. These chlorine-ammonia compounds are referred to as combined available chlorine (CAC) or combined residual chlorine (CRC). The sum of free and combined available/residual chlorine is called the total residual chlorine (TRC).

$$TRC = FAC + CAC = FRC + CRC \qquad (5)$$

The germicidal efficiency of free residual chlorine is directly related to the concentration of undissociated HOCl. Hypochlorous acid is 100 times more effective than the hypochlorite ion OCl^-. The fraction of undissociated HOCl increases with decreasing pH.

At pH = 7.5 (25°C, TDS = 40 mg/l), only 50% of free residual chlorine is present as HOCl, but 90% at pH = 6.5. The fraction of HOCl also increases with decreasing temperature. At 5°C, the HOCl mole fraction is 62% (pH = 7.5, TDS = 40 mg/l). In high salinity waters, less HOCl is present (30% at pH 7.5, 25°C, 40,000 mg/l TDS).

Chlorine demand

A part of the chlorine dosage reacts with ammonia nitrogen to combined available chlorine in a series of stepwise reactions:

$$HOCl + NH_3 \leftrightarrow NH_2Cl\ \text{(monochloramine)} + H_2O \qquad (6)$$

$$HOCl + NH_2Cl \leftrightarrow NHCl_2\ \text{(dichloramine)} + H_2O \qquad (7)$$

$$HOCl + NHCl_2 \leftrightarrow NCl_3\ \text{(trichloramine)} + H_2O \qquad (8)$$

These reactions are governed primarily by pH and chlorine-to-nitrogen weight ratio. Chloramine also has a germicidal effect, albeit lower than that of chlorine.
Another part of the chlorine is converted to nonavailable chlorine. This chlorine demand is caused by the reaction with reducing agents such as nitrite, cyanide, sulfide, ferrous iron and manganese. Chlorine is also consumed by the oxidation of organic compounds present in the water.

To determine the optimum chlorine dosage, best point of injection, pH and contact time to prevent biofouling, the ASTM method D 1291, “Standard Practice for Determining Chlorine Requirement of Water”, should be applied on a representative water sample. For further details, the Handbook of Chlorination[11] is recommended.

Sea water

The major difference of sea water chlorination chemistry in contrast to brackish water is the presence of bromide in sea water in concentrations of typically 65 mg/l. Bromide reacts rapidly with hypochlorous acid to hypobromous acid:

$$Br^- + HOCl \rightarrow HOBr + Cl^- \quad (9)$$

Thus, in chlorinated sea water the biocide is predominantly HOBr rather than HOCl.

Hypobromous acid then dissociates to hypobromite ions as follows:

$$HOBr \leftrightarrow OBr^- + H^+ \quad (10)$$

HOBr dissociation is less than HOCl dissociation. At pH 8, where only 28% of HOCl is undissociated, about 83% of HOBr is undissociated. In other words, effective disinfection can be performed at a higher pH than in brackish water, where no bromide is present.

Both hypobromous acid and hypobromite ions interfere with free residual chlorine measurements and are included in the free residual chlorine value.

The reactions of HOBr with other compounds of the water are analogous to the reactions of HOCl. Bromamines and brominated compounds are the reaction products.

3.6.4
Dechlorination

When FILMTEC® FT30 membrane is used in the reverse osmosis process, the RO feed must be dechlorinated to prevent oxidation of the membrane. FT30 membrane has some chlorine tolerance before noticeable loss of salt rejection is observed. Eventual degradation may occur after approximately 200-1,000 hours of exposure to one mg/l of free chlorine (200-1,000 ppm-h tolerance). The rate of chlorine attack depends on various feedwater characteristics. Under alkaline pH conditions, chlorine attack is faster than at neutral or acidic pH. An acidic pH is anyhow preferred for a better biocidal effect during chlorination. Chlorine attack is also faster at higher concentrations of heavy metals (e.g. iron), which catalyze membrane degradation, and at higher temperatures.

By comparison, some other polyamide RO membranes have essentially zero chlorine tolerance. The superior chlorine tolerance of the FT30 membrane can be attributed to the thicker barrier layer (about 2,000 Angstrom) and the fact that the polyamide is crosslinked. If dechlorination upsets occur in a FT30 RO system, and if corrected in a timely manner, membrane damage can be minimized.

For chloramine the tolerance of the FT30 membrane is 300,000 ppm-h, which implies that dechlorination is not required. However, since chloramines are formed by adding ammonia to chlorine, it is possible that free chlorine will be present. Since this free chlorine can be damaging to the membrane, dechlorination should still be considered.

Residual free chlorine can be reduced to harmless chlorides by activated carbon or chemical reducing agents.

An **activated carbon** bed is very effective in dechlorination of RO feed water according to following reaction:

$$C + 2\,Cl_2 + 2\,H_2O \rightarrow 4\,HCl + CO_2 \quad (11)$$

Sodium Metabisulfite (SMBS) is most common for removal of free chlorine and as a biostatic. Other chemical reducing agents exist, e.g. sulfur dioxide, but have not yet been proven cost-competitive with SMBS.

When dissolved in water, sodium bisulfite (SBS) is formed from SMBS:

$$Na_2S_2O_5 + H_2O \rightarrow 2\,NaHSO_3 \quad (12)$$

SBS is then reducing hypochlorous acid according to:

$$NaHSO_3 + HOCl \rightarrow HCl + NaHSO_4 \quad (13)$$

In theory, 1.34 mg of sodium metabisulfite will remove 1.0 mg of free chlorine. In practice however, 3.0 mg of sodium metabisulfite is normally used to remove 1.0 mg of chlorine.

Solid sodium metabisulfite has a usual shelf life of 4-6 months under cool, dry storage conditions. However, in aqueous solutions, sodium bisulfite can oxidize readily when exposed to air. A typical solution life can vary with concentration as follows:

(wt.%)	Solution Life
10	1 week
20	1 month
30	6 months

The SMBS should be of food grade quality and free of impurities. SMBS should not be cobalt-activated.

Although the dechlorination itself is rapid, good mixing is required to ensure completion; static mixers are recommended. The injection point is preferably downstream of the cartridge filters in order to have these protected by chlorine. In this case, the SMBS solution should be filtered through a separate cartridge before being injected into the RO feed. Dechlorinated water must not be stored in tanks.

The absence of chlorine should be monitored using an oxidation-reduction potential (ORP) electrode downstream of the mixing line. The electrode signal shuts down the high pressure pump when chlorine is detected.

3.6.5
Shock Treatment

Shock treatment is the addition of a biocide into the feed stream during normal plant operation for a limited time period. Sodium bisulfite is the most commonly used biocide for this purpose. In a typical application, 500-1,000 mg/l $NaHSO_3$ are dosed for 30 minutes.

The sodium metabisulfite should be food grade, free of impurities and not cobalt-activated. The treatment can be carried out on a periodic basis, e.g. every 24 hours, or only when biogrowth is suspected. The efficiency of such treatment should be studied. The permeate produced during dosage will contain 1-4% of the bisulfite feed concentration. Depending on the permeate quality requirements, the permeate can be used or discarded during shock treatment.

Bisulfite is more effective against aerobic bacteria than against anaerobic microorganisms. Therefore, the efficiency of the shock treatment should be carefully assessed using the techniques described in Section 3.6.2.

3.6.6
Sanitation

Instead of continuously adding a biocide to the raw water, biofouling can be controlled by periodic sanitations of the system. This is usually practiced in medium risk applications. In high risk applications, sanitations may be an additional measure to a continuous biocide dosing.

Preventive sanitations are much more effective than corrective disinfections, because single attached bacteria are easier to kill and remove than a thick, aged biofilm.

Typical sanitation intervals are one per month, but they can be as short as one per day, depending on the feed water quality (e.g. waste water) or the permeate quality required (e.g. pharmaceutical grade water). The membrane life however, may be shortened by extensive sanitations, depending on the type of chemical (see Section 7.7, Disinfecting RO Systems).

3.6.7
Other Methods

Microfiltration/Ultrafiltration offers advantages in that it can remove microorganisms and especially algae, which are sometimes very difficult to remove by standard techniques. The MF/UF membranes should be made from a chlorine-resistant material to withstand periodic sanitation.

Copper sulfate can also be used to control the biogrowth. Typically, copper sulfate is fed continuously at 0.1 to 0.5 mg/l concentrations. The generalized use of copper sulfate is however, not recommended due to the following:

- Commercial $CuSO_4$ may contain some impurities detrimental to the RO membranes.
- $CuCO_3$ and $Cu(OH)_2$ tend to precipitate outside of a given pH range of operation, causing fouling to RO devices, and making $CuSO_4$ ineffective.
- Copper ions can have negative effects on the environment.
- $CuSO_4$ only works properly against a limited range of microorganisms (e.g. some algae) but has only a marginal effect on most bacteria.
- Environmental protection standards of several countries limit the discharge amount of Cu salts, making it difficult to change dosage of this chemical if the biolife situation of a given plant requires it.

Ozone is an even stronger oxidizing agent than chlorine. However, it decomposes readily. A certain ozone level must be maintained to kill all microorganisms. The resistance of the materials of construction against ozone has to be considered. Usually, stainless steel is employed. De-ozonation must be performed carefully to protect the membranes. Ultraviolet irradiation has been used successfully for this purpose.

Ultraviolet irradiation at 254 nm is known to have a germicidal effect. Its application has come into use especially for small-scale plants. No chemicals are added, and the equipment needs little attention other than periodic cleanings or replacement of the mercury vapor lamps. UV treatment is limited however, to relatively clean waters, because colloids and organic matter reduce the penetration of the radiation.

Sodium bisulfite concentrations in the range of up to 50 mg/l in the feed stream of sea water RO plants have proven effective to control biological fouling. Colloidal fouling has also been reduced by this method. As a side benefit, no acid is required for calcium carbonate control because of the acidic reaction of bisulfite:

$$HSO_3^- \rightarrow H^+ + SO_3^{--} \qquad (14)$$

Granular activated carbon (GAC) filtration as pretreatment method is known to be a risk of releasing bacteria which might cause biofouling of the membranes. The high inner surface of the carbon pores together with adsorbed organic nutrients promote biological activity in the filter. However, when such filters are operated at sufficiently low filter velocities (2-10 m/h) and with sufficiently high beds (2-3 m), all the biolife activity takes place in the upper region of the filter bed, and the filtered water is almost free of bacteria and nutrients. This technique is widely used in public water works, where the biological activity of the carbon filter is further enhanced by ozonation of the feed, [1)].

The strategy of promoting biological growth in a restricted place where it is of no harm to the membranes, rather than trying to kill all microorganisms, might be a good approach to control biofouling of the membranes. However, there is little practical experience to date.

3.6.8
Pretreatment Design and Operation

To prevent biological fouling of the membranes, the entire system from the raw water intake up to the membranes has to be kept clean and in a sanitary state. Please refer to section 6.8, Control of Microbiological Activity, for more details.

3.7 Prevention of Fouling by Organics

Adsorption of organic substances on the membrane surface causes flux loss, which is irreversible in serious cases. The adsorption process is favored with high molecular mass compounds when these are hydrophobic or positively charged. A high pH value helps to prevent fouling, because both the membrane and many organic substances assume a negative charge at pH > 9. Organics present as an emulsion may form an organic film on the membrane surface, and must therefore be removed in the pretreatment.

Organics occurring in natural waters are usually humic substances in concentrations between 0.5 and 20 mg/l TOC. Pretreatment should be considered when TOC exceeds 3 mg/l. Humic substances can be removed by a coagulation process with hydroxide flocs (Sections 3.5.4 and 3.5.5), by ultrafiltration (Section 3.5.6), or adsorption on activated carbon.

Coagulation or activated carbon must also be applied when oils (hydrocarbons or silicone-based) and greases are contaminating the RO feed water at levels above 0.1 mg/l. These substances are readily adsorbed onto the membrane surface. They can be cleaned off however, with alkaline cleaning agents if the flux has not declined by more than 15%.

In waste water applications, the rejection and concentration of organics is a major objective. Depending on the kind of substances, organics even in the percent concentration range can be handled. This has to be evaluated in field tests on a case-by-case basis.

3.8 Prevention of Membrane Degradation

Apart from the fouling potential of certain substances in the RO feed water, the chemical resistance of the FT30 membrane element against such substances has to be taken into account. As a rule of thumb, all oxidizing agents can harm the membrane and must be removed by methods described in Section 3.6.4. The membrane element is stable against most other chemicals in a pH range of 2-11 as long as these chemicals are dissolved and not occurring as an organic phase.

3.9 Summary of Pretreatment Options

Table 1 summarizes the pretreatment options when specific risks for scaling and fouling are present. It is a quick reference for “possible” and “very effective” methods. The combination of “possible” methods may also be “very effective”.

Table 1

Pretreatment	$CaCO_3$	$CaSO_4$	$BaSO_4$	$SrSO_4$	CaF_2	SiO_2	SDI	Fe	Al	Bacteria	Oxid. Agents	Org. Matter
Acid Addition	●							❍				
Scale Inhibitor	❍	●	●	●	●	❍						
Softening with IX	●	●	●	●	●							
Dealkalization with IX	❍	❍	❍	❍	❍							
Lime Softening	❍	❍	❍	❍	❍	❍	❍	❍				❍
Preventive Cleaning	❍					❍	❍	❍	❍	❍		❍
Adjustment of Operation Parameter		❍	❍	❍	❍	●						
Media Filtration						❍	❍	❍	❍			
Oxidation-Filtration							❍	●				
In-Line-Coagulation							❍	❍	❍			❍
Coagulation-Flocculation						❍	●	❍	❍			●
Micro-/ Ultrafiltration						●	●	❍	❍	❍		●
Cartridge Filter						❍	❍	❍	❍	❍		
Chlorination										●		
Dechlorination											●	
Shock Treatment										❍		
Preventive Disinfection										❍		
GAC Filtration										❍	●	●

❍ Possible ● Very effective

3.10 References

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4. System Design

4.1 Introduction

An entire RO water desalination system consists of the pretreatment section, the desalination section, and the posttreatment section. Pretreatment techniques are discussed in Section 3. Posttreatment is employed to achieve the required product quality. In sea water desalination this is usually pH adjustment, rehardening and disinfection. In ultrapure water production, the permeate is usually posttreated by polishing ion exchange demineralization.
In this section, the desalination system is addressed. It includes a set of membrane elements, housed in pressure vessels which are arranged in a certain manner. A high pressure pump is used to feed the pressure vessels. Instrumentation, spare parts and tools for services are added as required. A cleaning-in-place (CIP) system facilitates the cleaning of the membranes. This is described in Section 7. The desalination system is a complete plant with an inlet for feed water and outlets for permeate and concentrate. RO system performance is typically characterized by two parameters, permeate (or product) flow and salt rejection. These should always be referenced to a given feed water analysis, feed pressure and recovery. The goal of the designer of an RO system for a certain required permeate flow is to minimize feed pressure and membrane costs while salt rejection and recovery should be maximized. The optimum design depends on the relative importance of these aspects.
The recovery of brackish water systems is limited by the solubility of sparingly soluble salts (see Section 3.4): 85% is about the maximum. In sea water desalination, the limit of 35-45% recovery is dictated by the osmotic pressure of the concentrate stream, because the physical limit of the FILMTEC® Sea Water Element is reached at 69 bar (1,000 PSI).
Obtaining the requested salt rejection is mainly a matter of membrane selection. The BW (Brackish Water), SW (Sea Water), and SWHR (Sea Water High Rejection) versions of the FT30 membrane have higher salt rejections in this order, but they also need higher feed pressures under same conditions. Therefore, the FT30 BW membrane is typically applied to feed waters up to 5,000 mg/l TDS, FT30 SW from 5,000 to 15,000 mg/l, and FT30 SWHR from 15,000 to 45,000 mg/l. For given operating conditions, the permeate quality can be calculated (see Section 4.11, System Performance Projection).
The feed pressure needed to produce the required permeate flow depends, for a given membrane, on the designed permeate flux [1]. The higher the permeate flow per unit of active membrane area, the higher the feed pressure.
While in sea water systems the permeate flux is relatively low even at maximum allowed pressure, the permeate flux could be very high in brackish water systems without reaching the limit of 41 bar for brackish water elements. Although it is tempting to increase the permeate flux in order to minimize the costs for membrane elements, the flux has to be limited in order to avoid fouling and scaling. From experience, the flux limit to be used in system design depends on the fouling tendency of the feed water.
The concentration of the fouling materials at the membrane surface increases with increasing permeate flux and increasing element recovery [2]. A system designed with high permeate flux rates is therefore likely to experience higher fouling rates and more frequent chemical cleaning.
The Silt Density Index (SDI) value of the pretreated feed water correlates fairly well with the amount of fouling material present.
Only experience can set the limits on permeate flux and element recovery for different types of waters.
When designing a membrane system for a specific feed water, it is advantageous to know the performance of other membrane systems operating on the same water. However, quite often there are no other membrane systems to compare with; and then the system design guidelines (Table 1) should be followed.

These guidelines are based on the assumption of a continuous process with a welldesigned and operated pretreatment system, and about four cleanings per year. Exceeding the recommended limits will result in more frequent cleanings and a reduced membrane life.

Further information required to design a system is best collected by using the forms of Table 2: “System Design Information” and Table 3: “Water Analysis for Reverse Osmosis”. The more complete this information, the better the system design can be optimized towards the customer's needs.

---

[1] **Permeate flux:** permeate flow rate per unit membrane area.

[2] **Element recovery:** ratio of permeate flow rate to feed flow rate for a single element.

Table 1: System Design Guidelines

Feed Source	Typical Membrane Active Area (ft^2)	RO/UF Permeate	Well Water/ Softened Supply	Softened Surface Supply	Surface Supply	Filtered Tertiary Effluent	Sea Water
Feed Silt Density Index		SDI < 1	SDI < 3	SDI 3 - 5	SDI 3 - 5		SDI < 5
Max. Element Recovery % 1m (40") Long Element		30	19	17	15 $^{1)}$	10	10 $^{1)}$
Max. Permeate Flow Rate per Element m^3/d (GPD)							
2.5" Diameter	23	700 (2.7)	600 (2.7)	500 (1.9)	500 (1.9)	300 (1.3)	500 (1.9)
4" Diameter							
BW30-4040 (obsolete)	70	2200 (8.3)	1800 (6.8)	1600 (6.1)	1500 (5.6)	1000 (3.8)	
BW30/NF70-4040	82	2570 (9.7)	2110 (8.0)	1870 (7.1)	1755 (6.6)	1170 (4.4)	
SW30/SW30HR-4040	68	2200 (8.3)	1800 (6.8)	1600 (6.1)	1500 (5.6)	1000 (3.8)	1500 (5.6)
8" Diameter							
BW30-330	330	9000 (33)	7500 (28)	6500 (25)	5900 (22)	4000 (15)	
BW30/NF70-345	345	9400 (36)	7840 (30)	6790 (27)	6160 (23)	4180 (16)	
BW30/NF70/NF90-400	400	10970 (42)	9140 (24)	7920 (30)	7190 (27)	4870 (19)	
SW30/SW30HR-8040	298	9000 (24)	7500 (28)	6500 (25)	5900 (22)	4000 (15)	6000 (22)
SG30-8040	320	8700 (33)	7270 (28)	6300 (24)	5720 (22)	3870 (15)	6000 (22)
Max. Feed Flow Rate per Element, U.S. gpm (m^3/h)							
2.5" Diameter		6 (1.3)	6 (1.3)	6 (1.3)	6 (1.3)	6 (1.3)	6 (1.3)
4" Diameter		18 (4.1)	18 (4.1)	18 (4.1)	18 (4.1)	18 (4.1)	18 (4.1)
8" Diameter (except as listed below)		70 (16)	62 (14)	60 (14)	55 (12)	50 (11)	60 (14)
BW30/NF70-345		73 (17)	65 (15)	63 (14)	58 (13)	52 (12)	63 (14)
BW30/NF70/NF90-400		85 (19)	75 (17)	73 (17)	67 (15)	61 (14)	73 (17)
Min. Concentrate Flow Rate per Element U.S. gpm (m^3/h)$^{1)}$							
2.5" Diameter		0,5 (0.11)	1 (0.22)	1 (0.22)	1 (0.22)	1 (0.22)	1 (0.22)
4" Diameter		2 (0.5)	4 (0.9)	4 (0.9)	4 (0.9)	4 (0.9)	4 (0.9)
8" Diameter		8 (1.8)	16 (3.6)	16 (3.6)	16 (3.6)	16 (3.6)	16 (3.6)

At permeate flow rates lower than shown in the column for Filtered Tertiary Effluent, maximum element recovery is 20% for surface water and 15% for sea water.
Note: The limiting values listed above have been incorporated into the ROSA (Reverse Osmosis System Analysis) software. Design of system in excess of the guidelines results in a warning message on the ROSA printout.

$^{1)}$We recommend that minimum concentrate flow rates be increased at the discretion of the designer by 20 % for feedwaters known to be high in fouling tendency (SDI > 3).

Table 2: System Design Information

Quotation No.: .... Date Requested: ....
Date Submitted: .... Requested by: ....

Customer/OEM: ....
Address: ....
Proposed Location: ....
Brief Description: ....
....
....
....

Required Product Flow Rate (m^3/h or GPD): ....
Expected Recovery: ....

Water Temperature on Site - Summer °C: ....
- Winter °C: ....
- Design °C: ....

RO-Plant: ☐ Indoors ☐ Outdoors

Designed for Continuous Use: ☐ Yes ☐ No
If not, please state needed peak hourly capacity: ....

Plant Will Be Operated by:
- Enduser ☐ Yes ☐ No
- Trained Personnel ☐ Yes ☐ No
- Equipment Manufacturer ☐ Yes ☐ No
- Others ☐ Yes ☐ No

Water Source:
- Well Water ☐
- Surface Water ☐
- Sea Water ☐
- Softened Water ☐
- Filtered Effluent Water ☐
- Others ☐

Existing Pretreatment: ☐ Yes ☐ No SDI ....
List of Pretreatment Steps: ....
....

Planned Pretreatment: ....

Bacterial Control: ☐ Yes ☐ No
Chlorine Used: ☐ Yes ☐ No
Chloramines Used: ☐ Yes ☐ No

Dechlorination:
- AC-Filter ☐
- Na-Bisulfite ☐
- Other ☐

☞ ☞ ☞

Table 2: System Design Information (continued)

Antiscalant Used: ☐ Yes Which One? ....
☐ No

Desired Acidification:
- HCl ☐
- H_2SO_4 ☐
- None ☐

Brief Description of Other Pretreatment Steps: ....
(e.g. Clarification, Flocculation, Multimedia/Sand Filtration etc.) ....
....

Application: ☐ Potable Water
☐ Industrial Supply for:
☐ Boiler Feed ☐ Pharma ☐ Electronics ☐ Other

Specify Water Quality Needed after RO Treatment::...
....

State Other Desired Design Criteria: ....
....
....
....

Table 3: Water Analysis for Reverse Osmosis

Sample identification: ....

Feed source: ....

Conductivity: .... pH: .... Temperature (°C): ....

Feed water analysis [1]:

NH_4^+ : ....

K^+ : ....

Na^+ : ....

Mg^{++} : ....

Ca^{++} : ....

Ba^{++} : ....

Sr^{++} : ....

Fe^{++} : ....

Fe (tot) : ....

Mn^{++} : ....

CO_2 : ....

CO_3^{--} : ....

HCO_3^- : ....

NO_3^- : ....

Cl^- : ....

F^- : ....

SO_4^{--} : ....

PO_4^{--} : ....

S^{--} : ....

SiO_2 (colloidal) : ....

SiO_2 (soluble) : ....

Other ions: ....

TDS (by method): ....

TOC: ....

BOD: ....

COD: ....

Total alkalinity (m-value): ....

Carbonate alkalinity (p-value): ....

Total hardness: ....

Turbidity (NTU): ....

Silt density index (SDI): ....

Bacteria (count/ml): ....

Free chlorine: ....

Remarks: ....

(odor, smell, color, biological activity, etc.:) ....

....

....

Analysis by: ....

Date: ....

---

[1] Please give units (mg/l as ion or ppm as $CaCO_3$ or meq/l)

4.2 Batch vs. Continuous Process

An RO system is usually designed for continuous operation. The operating conditions of every membrane element in the plant are constant with time. Figure 1 illustrates the continuous process mode.

In certain applications, when relatively small volumes (batches) of special feed waters occur discontinuously, e.g. waste water or industrial process solutions, the batch operation mode is preferred. The feed water is collected in a tank and treated subsequently. The permeate is removed and the concentrate is recycled back to the tank. At the end of the batch process, a small volume of concentrate remains in the feed tank. After this has been drained, the membranes are typically cleaned before the tank is filled again with a new batch. Figure 2 shows the batch operation mode.

A modification of the batch mode is the semi-batch mode. The feed tank is refilled with feed water already during operation. The batch is terminated with the feed tank full of concentrate. This allows a smaller tank to be used.

Batch systems are usually designed with a constant feed pressure and a declining permeate flow while the feed becomes more concentrated. The guidelines given in Section 4.1 should be applied to batch systems as well. The permeate flow limits however, are conservative and may be exceeded, if justified by preceding test runs, and if an appropriate cleaning frequency is taken into account.

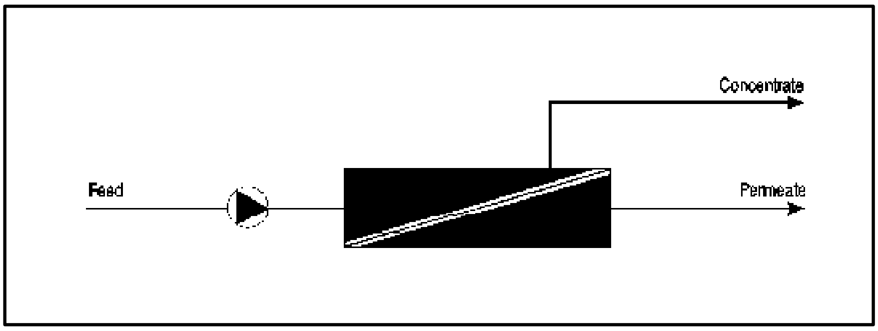

Figure 1: Continuous RO Process

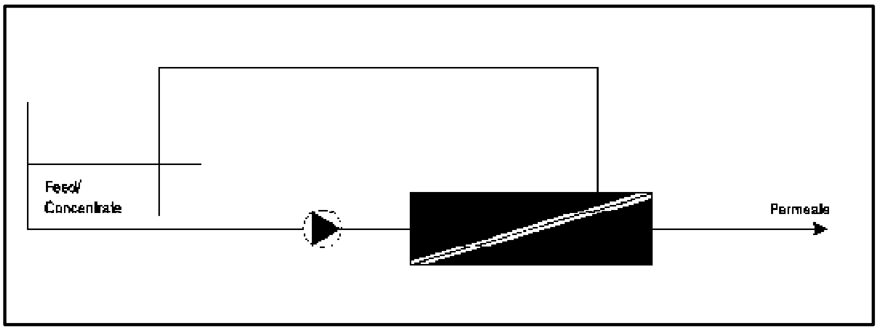

Figure 2: Batch RO Process

The batch process has following advantages versus the continuous process:

- Flexibility when the feed water quality changes
- System recovery can be maximized batch by batch
- Cleaning is easily implemented
- Simple automatic controls
- Permeate quality can be controlled by termination of the process
- Permeate quality can be improved by total or partial second pass treatment
- Favorable operating conditions for single (or low number) element systems, because the membranes are only in contact with the final concentrate for a short time
- Expansion is rather easy
- Less investment costs

The disadvantages are:

- No continuous permeate flow
- No constant permeate quality
- Large feed tank required
- Larger pump required
- Larger power consumption
- Longer residence time for feed/concentrate
- Higher total running costs

The majority of RO systems are designed for continuous operation with constant permeate flow and constant system recovery. Variations in feed water temperature and fouling effects are compensated by adjusting the feed pressure. The focus of this handbook is therefore on the continuous process.

4.3 Single-Module System

A module consists of a pressure vessel with up to seven membrane elements, which are connected in series. The concentrate of the first element becomes the feed to the second, and so on. The product tubes of all elements are coupled and connected to the module permeate port. The permeate port may be located on the feed end or on the concentrate end of the module.

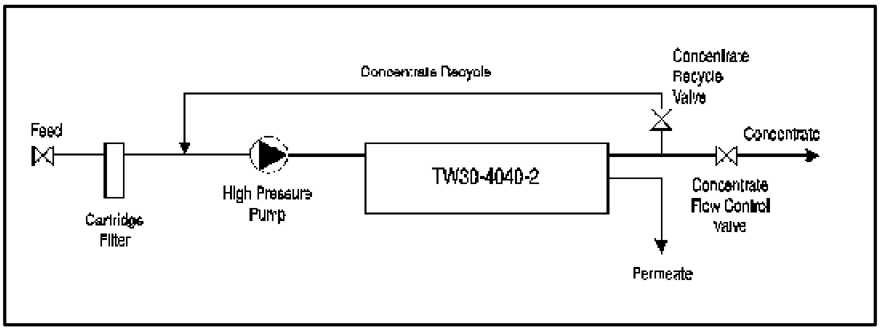

Figure 1: Single-Module System

Singlemodule systems are chosen when only one or few membrane elements are needed for the specified permeate flow. Figure 1 shows a system example with a module containing 2 FILMTEC® Tapwater Elements TW30-4040.

Feed water enters the system through the shut-off valve and flows through the cartridge filter to the high pressure pump. Alternate means of controlling pump discharge pressure are described in Section 4.12.1, High Pressure Pump.

From the high pressure pump, the feed water flows to the feed inlet connection of the module. The product stream should leave the module at no more than 0.3 bar (5 PSI) over atmospheric pressure. Sometimes however, a higher permeate pressure is required, e.g. to feed the post-treatment section or to distribute the product without further pumping. Then the feed pressure has to be increased by the value of the permeate pressure, but the specified maximum feed pressure has to be observed.

In this case, extreme care must be exercised so that at any time, especially also at emergency shut downs, the permeate pressure does not exceed the feed pressure by more than 0.3 bar. The maximum permissible permeate pressure is a feature of the pressure vessel (see Section 4.12.2, Pressure Vessel).

The concentrate leaves the concentrate outlet connection at essentially the feed pressure. Pressure drop will usually amount to 0.3 to 2 bar (5-30 PSI) from feed inlet to concentrate outlet, depending on the number of membrane elements, the feed flow velocity and the temperature. The concentrate flow rate is controlled by the concentrate flow control valve.
The system recovery is controlled by this valve and must never exceed the design value.

In singlemodule systems, concentrate recycling is usually required to comply with the guidelines for element recovery. To achieve system recoveries of more than 50%, a part of the concentrate leaving the module goes to drain, while the other part is added to the suction side of the high pressure pump, thus increasing the feed flow to the module. A high fraction of the concentrate being recycled helps to reduce the element recovery and thus the risk of fouling. On the other hand, it has the following drawbacks:

- Larger (more expensive) high pressure pump.
- Higher energy consumption.
- Permeate quality decreases with more concentrate being added to the feed water.
- The rinse-out time at start-up after preservation or cleaning can be long. Preferably, no concentrate should be recycled during the rinse-out period.

4.4 Single-Array System

In a single-array system, two or more modules are arranged in parallel. Feed, product and concentrate are connected to manifolds. Other aspects of the system are the same as in a single-module system. Single-array systems are typically used where the system recovery is less than 50%, e.g. in sea water desalination.

An example of a single-array system is outlined in Figure 1: Each of the three pressure vessels houses six FILMTEC® elements SW30HR-8040.

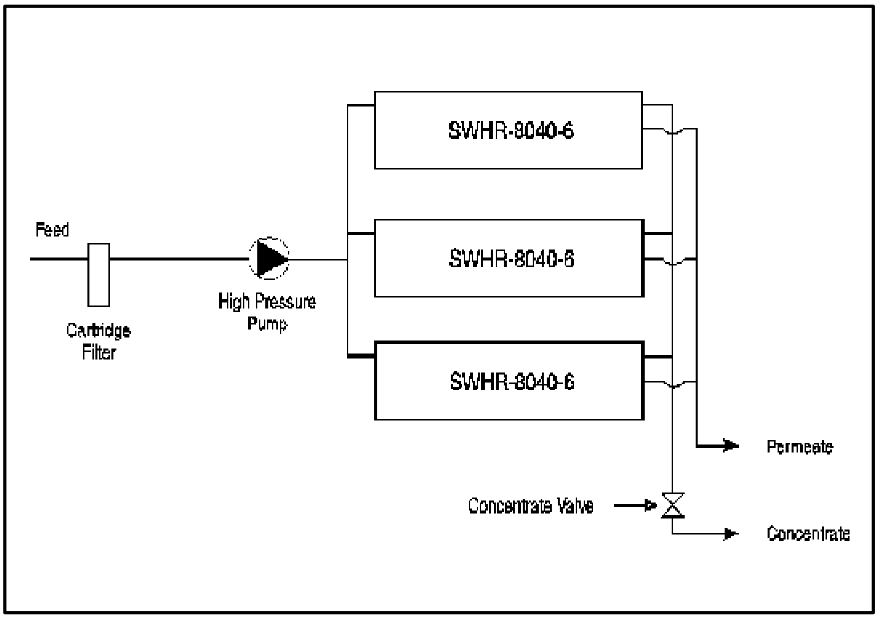

Figure 1: Single-Array System

4.5 Multi-Array System

Systems with more than one array or stage are used for higher system recoveries without exceeding the single element recovery limits. Usually two arrays will suffice for recoveries up to 75%, and three must be used for higher recoveries. These numbers are based on the assumption that standard pressure vessels with six elements are used. For shorter vessels housing only three elements, for example, the number of arrays has to be doubled for the same system recovery. Generally speaking, the higher the system recovery, the more membrane elements have to be connected in series. In order to compensate for the permeate that is removed and to maintain a uniform feed flow to each array, the number of pressure vessels per array decreases in the direction of feed flow.

A typical two-array system using a staging ratio of 2:1 is shown in Figure 1. The staging ratio is defined as the ratio of pressure vessels in two adjacent arrays, upstream vessels: downstream vessels.

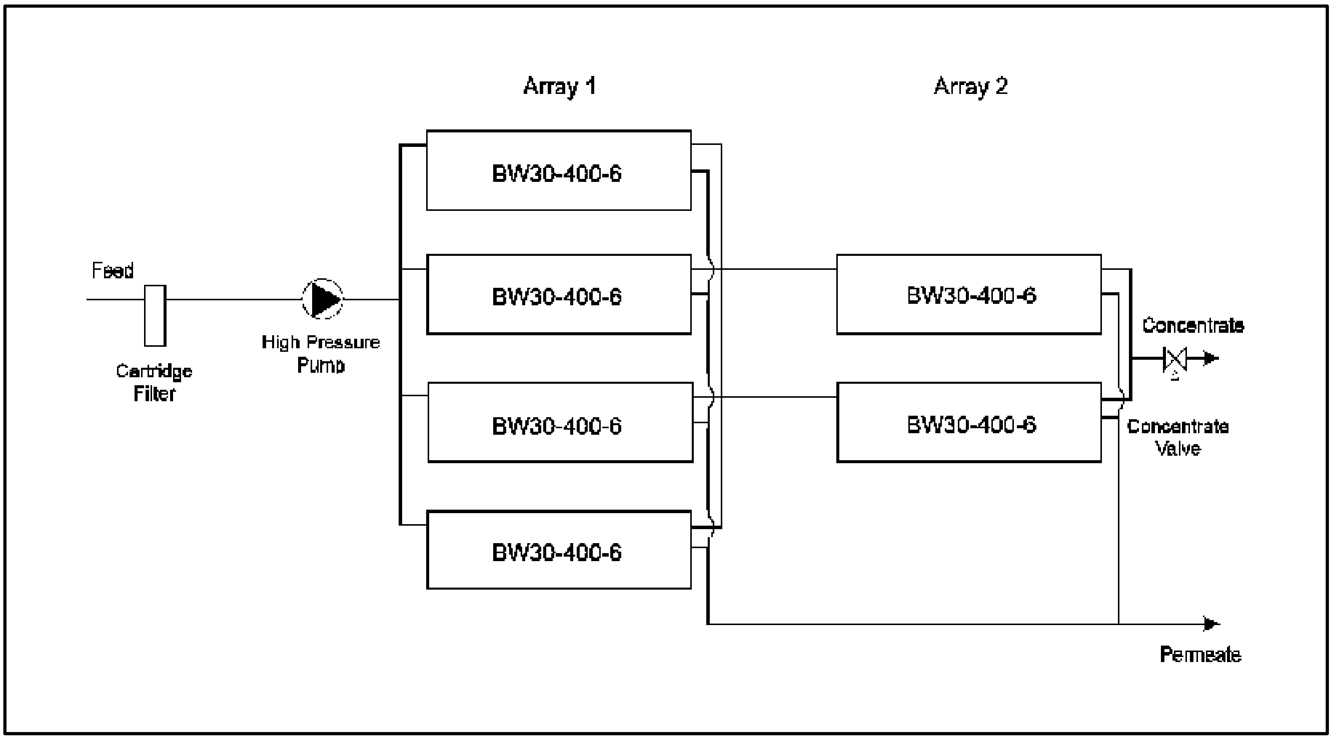

Figure 1: Two-Array System

5.6 Plug Flow vs. Concentrate Recirculation

The standard reverse osmosis system design for water desalination applications is the plug flow concept.

In a plug flow system, the feed volume is passed once through the system. A certain fraction Y of the feed passes across the membrane to produce permeate. The feed is gradually concentrated and leaves the system at a higher concentration. Examples of plug flow systems are shown in Figure 1 of Section 4.2, Figure 1 of Section 4.4 and Figure 1 of Section 4.5.

Concentrate recirculation is employed when the number of elements is too small to achieve a sufficiently high system recovery with plug flow. Concentrate recirculation systems can also be found in special applications like process liquids and wastewaters.

In systems with internal concentrate recirculation, a fraction of the concentrate stream out of the module (or array) is directed back to the feed side of the module (or array) and mixed with the feed stream. Figure 1 of Section 4.3 shows a system with internal concentrate recirculation.

Multi-array systems can also be designed with internal concentrate recirculation for each array, using a separate recirculation pump. For example, the system shown in Figure 1 of Section 4.5 can be designed with concentrate recirculation instead of plug flow: see Figure 1.

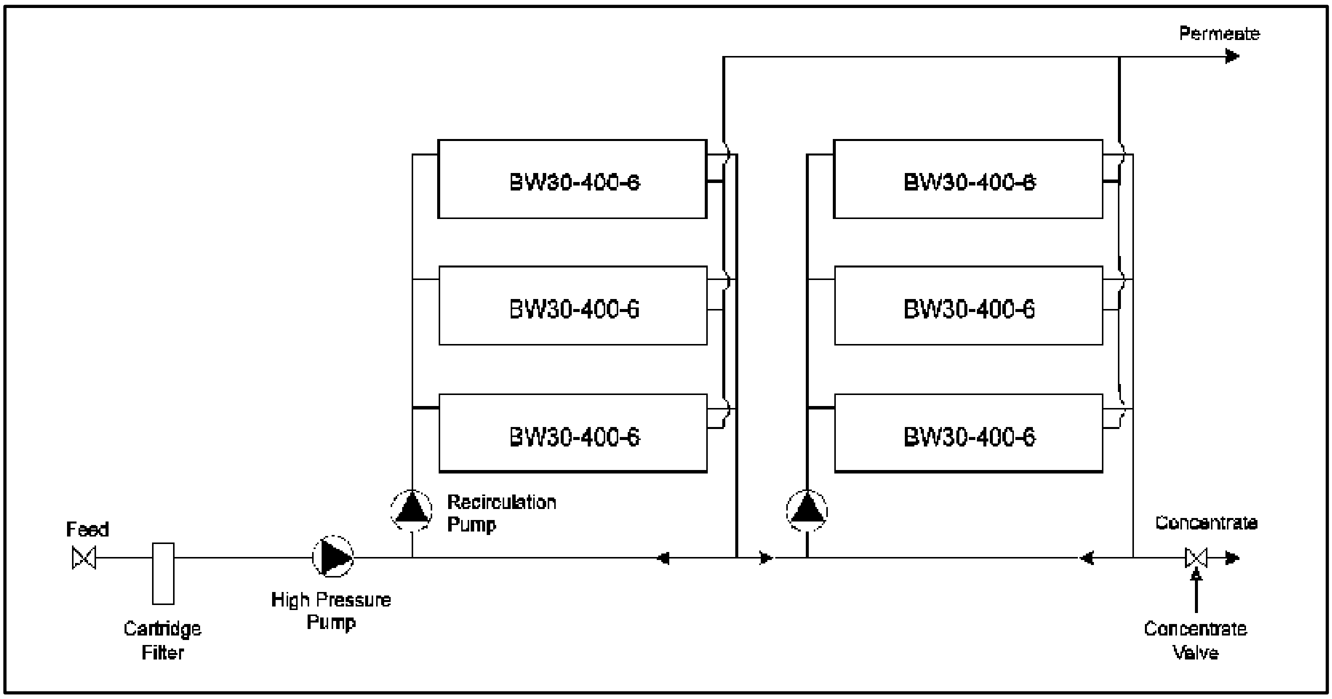

Figure 1: Two-Array System with Internal Concentrate Recirculation

The main advantage of the recirculation concept is the defined feed flow rate to the modules regardless of the degree of fouling of preceding modules, and regardless of changes in the feed water composition. Further aspects of the recirculation concept are mentioned in Sections 4.2 and 4.3. A comparative summary is given in Table 1.

The apparent salt passage SP_s of the system, also called system salt passage, is defined as the concentration of a compound (may be a certain ion, an organic compound, or TDS) in the permeate (C_p) related to its concentration in the feed water (C_f):

$$SP_s = \frac{C_p}{C_f} \qquad (1)$$

In plug flow systems, SP_s is a function of the system recovery Y and the membrane salt passage SP_M:

$$SP_s = \frac{1-(1-Y)^{SP_M}}{Y} \qquad (2)$$

where the membrane salt passage is defined as the concentration of a compound in the permeate (C_p) related to its average concentration on the feed-concentrate side (C_{fc}):

$$SP_M = \frac{C_p}{C_{fc}} \qquad (3)$$

In systems with internal concentrate recirculation, however, there is an additional dependence on the ß number, which is defined as

$$ß = \frac{\text{permeate flow leaving the module}}{\text{concentrate flow leaving the module}} \qquad (4)$$

For systems with the concentrate being partly recycled to the feed stream, the system salt passage is

$$SP_s = \frac{(1+ß)^{SP_M} - 1}{Y\,(1+ß)^{SP_M} - Y\,(1+ß) + ß} \qquad (5)$$

Table 1: Comparison of Plug Flow and Recirculation Systems

	Plug Flow	Recirculation
Feed Composition	must be constant	can vary
System Recovery	must be constant	can vary
Cleaning Circuit	more complicated	simple
Compensating Fouling	more difficult	easy
Membrane Pressure from Feed Inlet to Concentrate End	decreasing	uniform
Power Consumption	lower	higher (15-20%)
Number of Pumps (Investment, Maintenance)	lower	higher
Extension, Varying the Membrane Area	more difficult	easy
Taking Individual Arrays of Multi-Array Systems in/out of Service	not possible	possible
System Salt Passage	lower	higher

Especially for high system recoveries, the system salt passage of a recirculation system is much higher than of a plug flow system. This is demonstrated by a sample calculation, see Figure 2. The difference is less, however, for multi-array systems with recirculation loops for each array. The system salt passage of such a system (for an example see Figure 1) has to be calculated by application of equation (5) to each array.
When the recirculated concentrate stream approaches zero, the ß number approaches 1/((1/Y) –1), and the recirculation system becomes a plug flow system.
A compromise between plug flow and recirculation systems is the tapered recirculation system with a declining number of parallel modules per array when viewed in feed flow direction (see Figure 3).

The recirculation pumps can be tailored in such a way that only a minor part of the concentrate leaving the array is recycled while the major part is flowing to the next array (or to the concentrate outlet, for the last array). Then, there are almost plug flow conditions, but the advantages of the recirculation concept are still present.

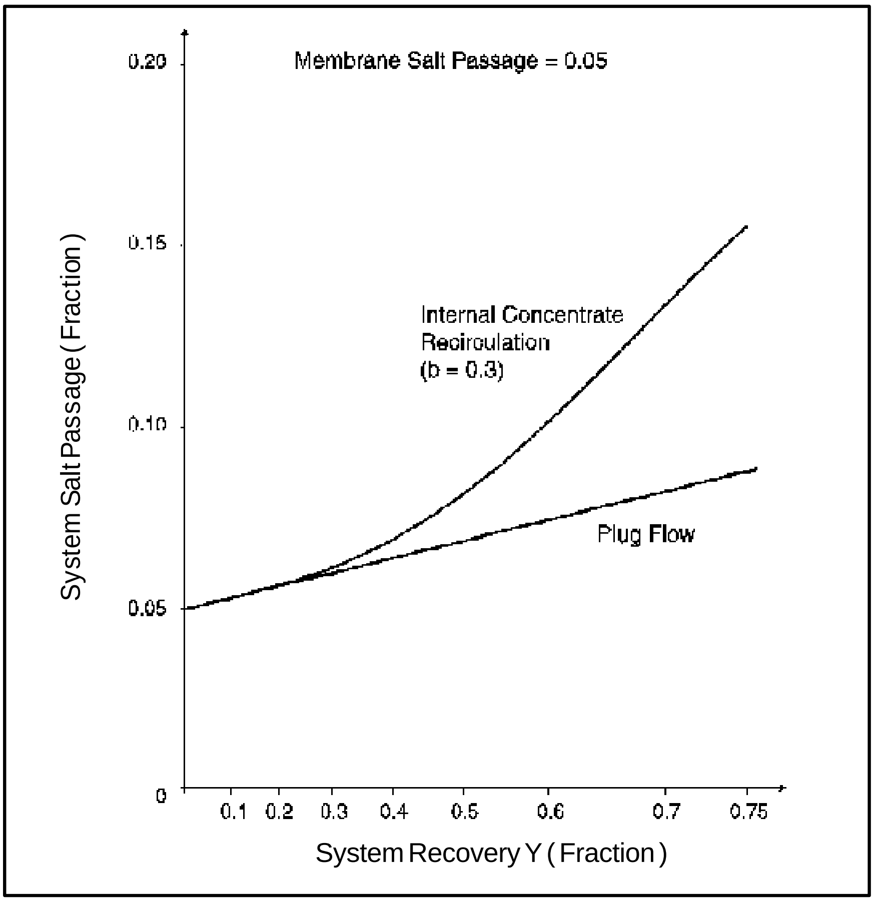

Figure 2: System Salt Passage for a Plug Flow and a Concentrate Recirculation System

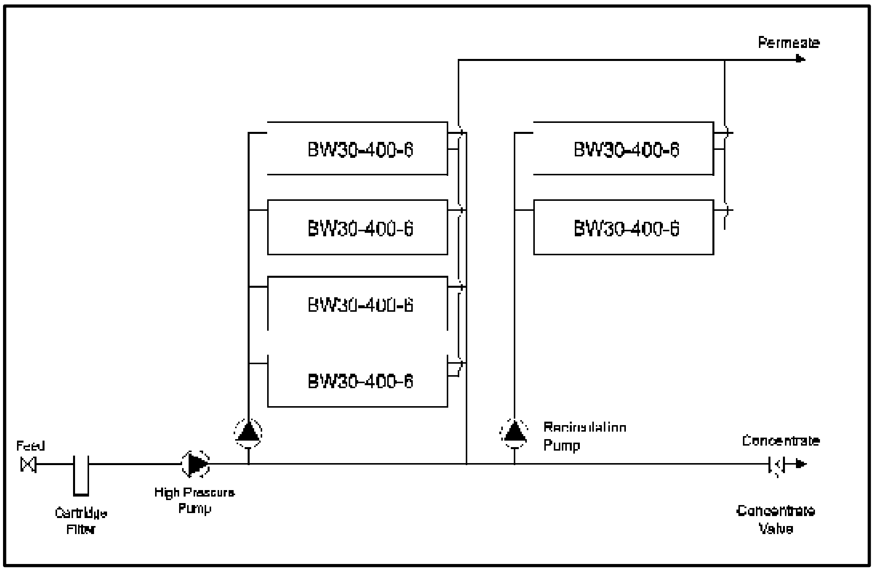

Figure 3: Tapered Recirculation System

4.7 Permeate Staged System

A permeate staged system may be considered for the following reasons:

- standard permeate quality is not sufficient
- post-treatment with ion exchange technology is not allowed (regeneration chemicals)
- rejection of bacteria, pyrogens and organic matter is most important
- high reliability

The production of water for pharmaceutical and medical use is a typical application of permeate staged systems.

A permeate staged system is the combination of two conventional RO systems where the permeate of the first system (first pass) becomes the feed for the second system (second pass). Both RO systems may be of the single-array or multi-array type, either with plug flow or with concentrate recirculation.

Figure 1 shows a schematic flow diagram of a permeate staged system.

The concentrate of RO II is recycled back to the feed of RO I, because its quality is usually better than the system feed water.

Since the feed water to RO II is of high quality (RO permeate), RO II can be designed for a higher recovery than RO I, and with fewer membrane elements (see Design Guidelines, Section 4.1).

Instead of having a separate high pressure pump for the second pass, the whole system can also be operated with one single high pressure pump, provided the maximum permissible feed pressure of the membrane element is not exceeded (41 bar (600 PSI) for BW elements).

The second pass is then operated with the permeate backpressure from RO I. For the maximum permeate backpressure allowed, please refer to Section 4.12.2. Care must be exercised, that the permeate backpressure at no time exceeds the feed pressure by more than 0.3 bar (5 PSI).

A surge tank can also be used to collect the permeate from the first pass. This tank must be carefully protected against dust and microbiological contamination.

The conductivity is in many cases the most important quality parameter of the product. Since carbon dioxide is not rejected by the membrane, it is present in the product, where it reacts to carbonic acid and causes the conductivity to increase. The passage of carbon dioxide can be prevented by alkalization of the feed water to pH 8.2. At this pH, all carbon dioxide is converted into hydrogen carbonate, which is well rejected by the membrane. Caustic soda can be injected either into the permeate of RO I or into the feed of RO I. In the first case, very little caustic is required, because there is almost no buffer capacity. Care must be taken not to overdose NaOH. In the second case, the feedwater must be carefully pretreated in order to prevent calcium carbonate scaling, which might otherwise easily happen at pH 8.2.

With this concept, a product conductivity of typically < 1 µS/cm can be achieved.

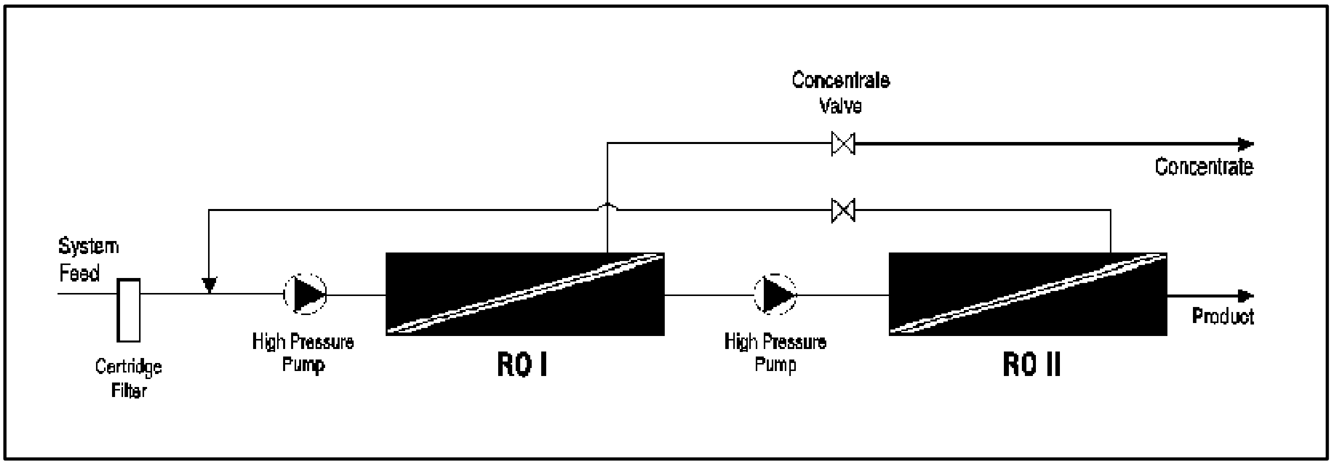

Figure 1: Permeate Staged System

4.8 Special Design Possibilities

There are a number of special design possibilities for specific requirements:

- **Improve product quality:**
    - ➔ Use part or all sea water elements for brackish feed water
    - ➔ Use sea water elements in one or both stages of a permeate staged system
    - ➔ Recycle permeate of last array into feed
- **Increase system recovery:**
    - ➔ Feed the concentrate to a second plant, after specific pretreatment
- **Obtain high system recovery and uniform permeate flow per element with medium salinity feed water:**
    - ➔ Use booster pumps between arrays to compensate for osmotic pressure increase
    - ➔ Use declining permeate back pressure from first to last array
    - ➔ Use SW or SWHR elements in the first array
- **Produce different permeate qualities:**
    - ➔ Separate the permeates from the different arrays: the permeate from the first array has the best quality – especially when the first array is equipped with sea water elements
- **Reduce the plant capacity to obtain just the required permeate quality:**
    - ➔ Blend the permeate with feed water
- **Make provisions for later system extension:**
    - ➔ Use free space in pressure vessel (spacer tube to replace element)
    - ➔ Design module support racks to accommodate extra pressure vessels

4.9 Element Type Selection

The FT30 membrane is available in three different grades, as SW30HR (Sea Water High Rejection), SW30 (Sea Water), and BW30 (Brackish Water). These membranes are used in spiral wound membrane elements, which have the same designation. In the tapwater element TW30, the BW30 membrane is used. Membrane elements are available in various diameters and lengths. Standard diameters are 2.5, 4.0 and 8.0 inch (64, 102 and 203 mm). The standard length is 40 inch (1,016 mm). For example the nomenclature of an 8 inch diameter, 40 inch long Brackish Water Element is BW30-8040. (Membrane surface area is sometimes used in place of diameter and length (i.e. BW30-400)

Table 1 shows the sizes and types of FT30 membrane elements.

Table 1: FT30 Membrane Element

Diameter (Inch)	Length (Inch)		Type		
		SW30HR	SW30	BW30	TW30
1.5	12				X
1.8	12				X
2.0	13				X
2.0	26				X
2.5	14	X	X	X	X
2.5	21	X	X	X	X
2.5	40	X	X	X	X
4.0	14			X	X
4.0	21	X	X	X	X
4.0	40	X	X	X	X
4.6	11				X
4.6	19				X
4.6	41				X
8.0	40	X	X	X	

To select the right element for a given purpose, there are several criteria to be considered [1]:

- Feed water TDS
  - < 1,000 mg/l → TW30
  - < 5,000 mg/l → BW30
  - 5,000-15,000 mg/l → SW30
  - 15,000-50,000 mg/l → SW30HR
- System salt rejection
  - > 92% → TW30
  - > 98% → BW30
  - > 99% → SW30
  - > 99% → SW30HR
- Required feed pressure
  - < 21 bar (300 PSI) → TW30
  - < 41 bar (600 PSI) → BW30
  - > 41 bar (600 PSI) → SW30, SW30HR
- System dimensions restricted
  - yes → element length < 40"
  - no → element length = 40"
- Required permeate flow
  - < 0.2 m^3/h (0.9 GPM) → element diameter ≤ 2.5"
  - < 3m^3/h (13 GPM) → element diameter = 4"
  - > 3m^3/h (13 GPM) → element diameter = 8"

Some applications, e.g. in the food and beverage industry, require a sanitary membrane element design. Many element sizes are available in a "full fit" (FF) configuration: these elements have a polypropylene net instead of an adhesive tape or a fiberglass wrapping and do not have a brine seal. Thus, there is no stagnant water between the element shell and the inner side of the pressure vessel.

Please contact your local Dow Sales Office for further information.

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[1] These recommendations are not binding, but suggestions to select the element for a system that has to be designed. The final choice depends also on specific requirements and operating conditions of the system.

4.10 Number of Elements and Pressure Vessels

RO systems are usually designed for a specified permeate flow Q_P. To achieve this flow, a number of membrane elements N_E is required. This section describes how the number of elements and pressure vessels required for a specified permeate flow and a specified feed water source can be estimated. With these figures, a system can be chosen. The chosen system must then be analyzed using the FILMTEC® Reverse Osmosis System Analysis (ROSA) computer program (see 4.11 page 7). This program calculates the feed pressure and the permeate quality of the system as well as the operating data of all individual elements. It is then easy to optimize the system design by changing the number and type of elements and their arrangement. The average permeate flow per membrane element, $\overline{Q}_{Pi}$ is:

$$\overline{Q}_{Pi} = \frac{Q_P}{N_E} \qquad (1)$$

The maximum allowed permeate flow per individual element, Q_{Pimax} depends on the feed water quality according to the System Design Guidelines (see Section 4.1). For a softened surface supply, for example. Q_{Pimax} is 25 m^3/d (6,500 GPD) for an eight inch element. This limit must not be exceeded by any element of the system. The lead elements are usually the critical ones with the higest permeate flows, because these experience the higest feed pressure and the lowest osmotic pressure of the feed water.

Brackish water systems are usually designed with the lead element(s) producing the maximum allowed permeate flow Q_{Pimax} according to the given feed water quality. The permeate flow of the other elements decreases in feed flow direction, because the feed pressure drops due to the flow resistance, and the osmotic pressure increases due to the concentration of rejected salts. In most standard applications, the average permeate flow per element, $\overline{Q}_{Pi}$ is about 75% of the maximum permeate flow, Q_{Pimax}:

$$\overline{Q}_{Pi} = 0.75 \times Q_{Pimax} \qquad (2)$$

Thus, the number of elements can be estimated from the chosen Q_{Pimax} value with equations (1) and (2):

$$N_E = \frac{Q_P}{0.75 \times Q_{Pimax}} \qquad (3)$$

The number of pressure vessels, N_V is obtained from:

$$N_V = \frac{N_E}{N_{EpV}} \qquad (4)$$

where N_{EpV} is the number of elements per pressure vessel. Standard vessels for big plants contain six elements. N_V is rounded to the next highest whole number.

For six-element vessels, the staging ratio is typically chosen as close to 2:1 as the whole number ratio of the vessel numbers of two successive arrays will allow. For vessels with less than six elements, the staging ratio will be less, for example 4:3:2 in a three-array system with four-element-vessels.

Example:

Given:	*Chosen:*
• Feed source: Brackish well water, softened, SDI < 3 • Required permeate flow: Q_P = 30 m^3/h = 720 m^3/d (132 GPM) • Six-element vessels to be used	• BW30-8040 element • Q_{Pimax} = 28 m^3/d (7500 GPD) (System Design Guidelines)
Estimated:	*Chosen:*
• N_E = 34.3 (from equation 3) • N_V = 5.7 (from equation 4)	• System with 6 pressure vessels in a 4:2 arrangement.

In **sea water** desalination systems the limiting parameter is usually not the permeate flow per element, but the feed pressure, which must not exceed 69 bar (1,000 PSI). The number of elements required for a specific system permeate flow Q_P can roughly be estimated from:

$$N_E = \frac{Q_P}{0.75 \times Q_{Pispec}} \qquad (5)$$

where Q_{Pispec} is the specified permeate flow per element under Sea Water Test Conditions, as given in the Technical Bulletin. From the number of elements, one can determine the number of pressure vessels as already described.

One array is usually sufficient for sea water systems with maximum 40% recovery.

4.11 System Performance Projection

4.11.1 System Operating Characteristics

Before a system performance projection is run, you should be familiar with the operating characteristics of a system. These will be explained using a typical example. Figure 1 shows a two-array system with three 6-element-pressure vessels using a staging ratio of 2:1.

Two-array systems with 6-element vessels effectively employ twelve spiral wound elements in series and are generally capable of operating at an overall recovery rate of 60 to 75%. For such systems the average individual recovery rate per element will vary from 7 to 12%. To operate a two-array system at an overall recovery much higher than 75% will cause an individual element to exceed the maximum recovery limits shown in the Design Guidelines of Chapter 4.1. When this happens, a third array will have to be employed which places eighteen elements in series shifting the average element recovery rate to lower values.

If two-array systems are operated at too low a recovery (e.g. < 60%), the feed flow rates to the first-array vessels can be too high causing excessive feed/concentrate-side pressure drops and potentially damaging the elements. For example, FILMTEC® 8040 elements have a maximum feed flow rate of 11 to 16 m^3/h (50-70 GPM) depending on water source (see System Design Guidelines, Section 4.1). As a result, systems with lower than 60% recovery will typically utilize single-array configurations. Maximum flow considerations can also limit the staging ratio. It is unlikely to find systems with staging ratios greater than 3:1.

When a single RO element is run, the operating variables are readily measured, and performance can be easily correlated. When a large number of elements are combined in a system with a complex series-parallel- series configuration and only inlet operating variables are known, system performance prediction becomes considerably more complex. Feed pressures and salt concentrations for each element in series are changing. The rate and extent of these changes are dependent not only on the inlet conditions and overall recovery, but also on the array configuration, i.e. staging ratio(s).

Figure 2 illustrates the dynamic nature of predicting system performance based on the sum of individual element performances within the system. It shows how five different element performance parameters vary throughout the twelve series positions in a 2:1 array of 6-element pressure vessels. The system is operating at 75% recovery and 25°C with a feed osmotic

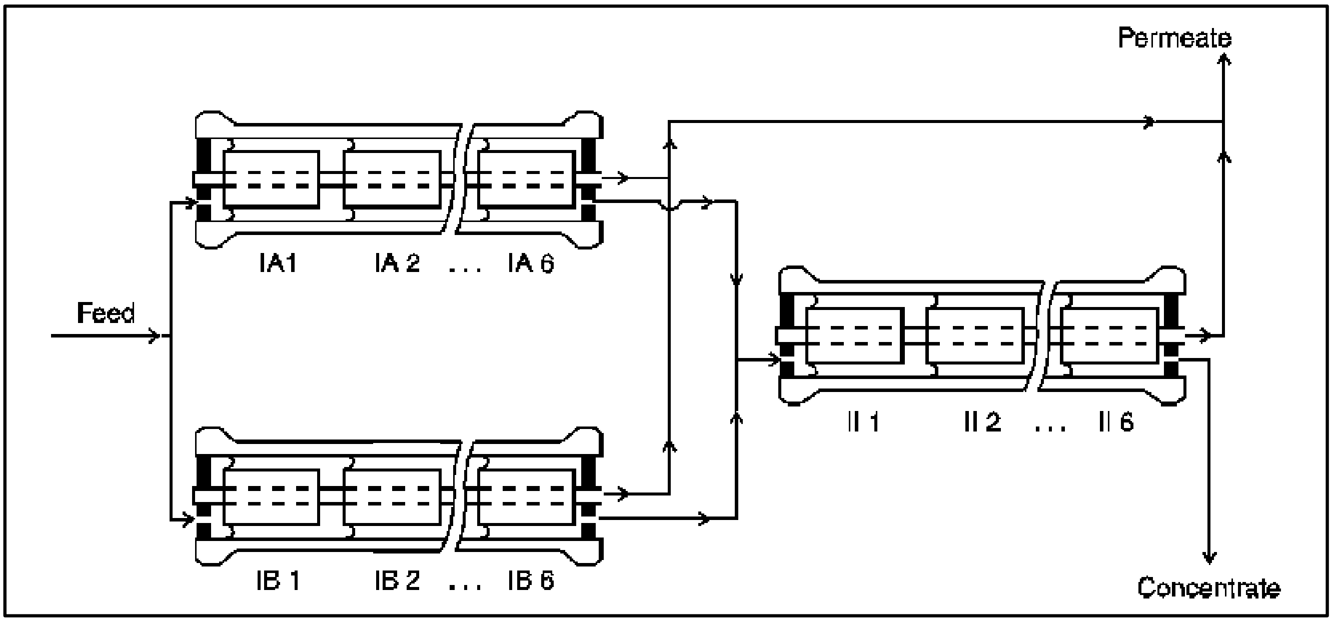

Figure 1: Typical Two-Array Staging Configuration for Spiral Wound RO Elements

pressure of 1.4 bar (20 PSI, which roughly corresponds to a 2,000 mg/l feed TDS). The inlet feed pressure has been adjusted so that the lead BW30-8040 element is producing 7500 gpd (28,4 m^3/d) (7,500 GPD), the maximum permeate flow for a well water system with feed SDI < 3.

The top third of Figure 2 shows individual element permeate flows decreasing uniformly throughout the series configuration from 28.4 m^3/d in the lead element of the first array to approximately 3300 gpd (12.5 m^3/d) in the last element of the second array. The average element permeate rate is 22m^3/d (5,800 GPD) or 77% of the maximum allowable limit.

Permeate flow decreases because the net permeation driving force, $\Delta P - \Delta\pi$, is uniformly declining. (ΔP is the pressure difference between the feed side and the permeate side of the membrane; $\Delta\pi$ is the osmotic pressure difference between both sides). This is evident by looking at the two curves in the bottom third of the figure. The upper curve shows how the inlet feed pressure to each element (P_{fi}) decreases due to the upstream concentrate-side pressure losses within each element.

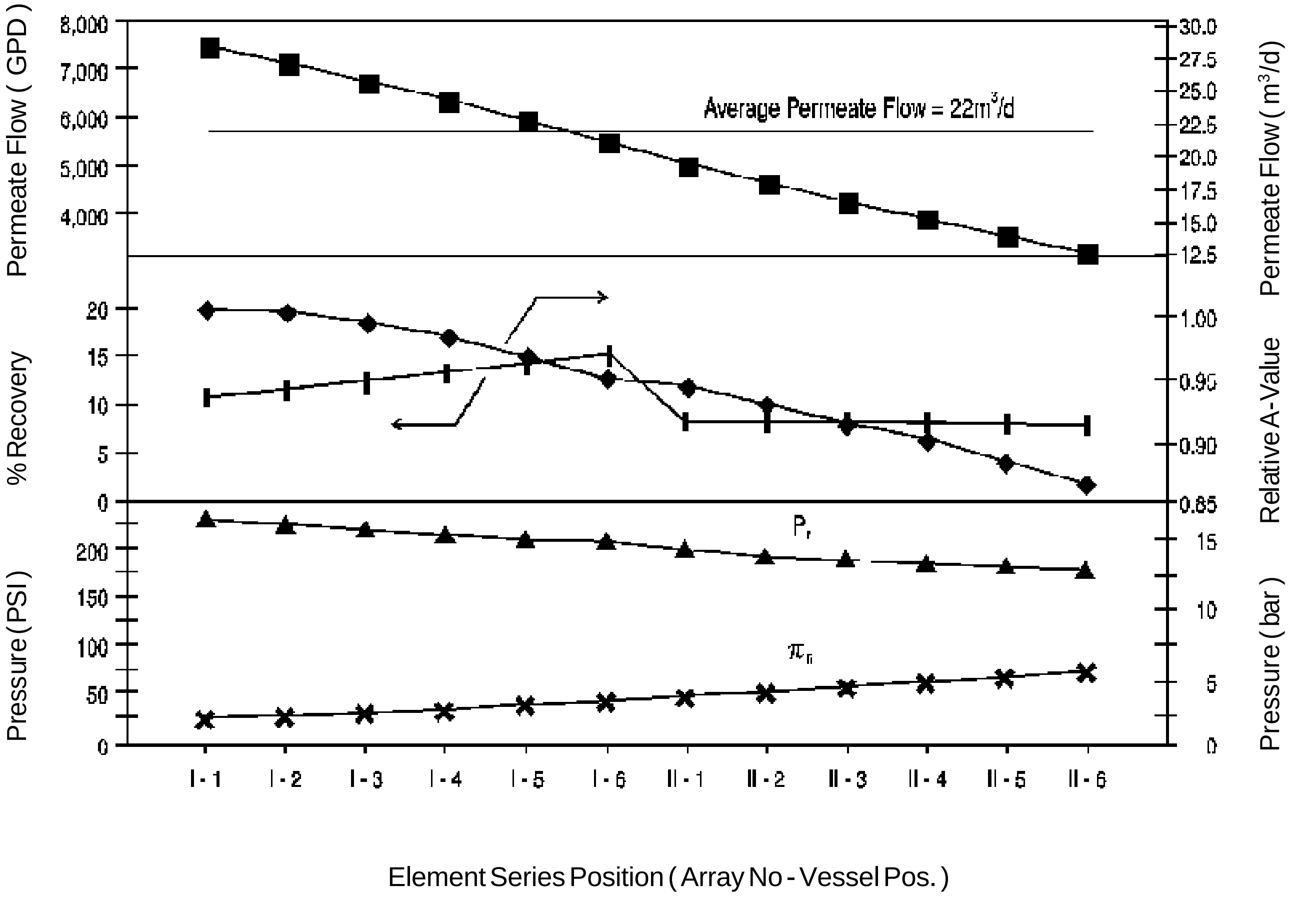

Figure 2: Individual Element Performance in a System 2:1 Array of BW30-8040 Elements (Example)

The bottom curve shows how the inlet feed osmotic pressure to each element (π_{fi}) is increasing as salt-free (mostly) permeate is progressively removed by each upstream element, leaving behind a steadily increasing concentrate concentration. The difference between these two pressure curves is roughly equivalent to the net permeation driving force.

The middle portion of Figure 2 exhibits two subtle but important effects. The left-hand scale shows how individual element recovery varies within the twelve element (series) sequence. The break occurs between the first and second arrays. In general, the individual recovery profile will increase in both arrays but typically more strongly in the first. The system designer – utilizing a computer program – must verify that the last element in the first array does not exceed the appropriate recovery limit. As element recovery increases, the effective osmotic pressure that the membrane “sees” will be higher due to concentration polarization. This inefficiency reduces permeate flows and can lead to membrane scaling or fouling if allowed to go to excess.

The other curve in the middle portion of Figure 2 (right-hand scale) illustrates an interesting phenomenon exhibited by the FILMTEC® FT30 membrane. It shows that the membrane water permeability coefficient, or A-value, is a reversible function of salt concentration, decreasing at higher salinities and increasing at lower salinities.
The water permeability declines by almost 15% in this example through the series of twelve elements, and this must be taken into consideration if an accurate design for system permeate flow rate is to be obtained.

Design Equations and Parameters

The performance of a specified RO system is defined by its feed pressure (or permeate flow, if the feed pressure is specified) and its salt passage. In its simplest terms, the permeate flow Q through an RO membrane is directly proportional to the wetted surface area S times a net permeation driving force ($\Delta P - \Delta\pi$). The proportionality constant is the membrane permeability coefficient or A-value. The familiar water permeation equation has the form:

$$Q = A \times S \times (\Delta P - \Delta\pi) \qquad (1)$$

The salt passage is by diffusion, hence the salt flux N_A is proportional to the salt concentration difference between both sides of the membrane. The proportionality constant is the salt diffusion coefficient or B-value.

$$N_A = B \times (C_{fc} - C_p) \qquad (2)$$

where C_{fc} = feed-concentrate average concentration
C_p = permeate concentration

There are basically two ways to calculate the performance of a specified design:

Element-to-Element
This is the most rigorous calculation method. It is too tedious for hand calculation, but it is suitable for computer calculations. All the operating conditions of the first element must be known, including the feed pressure.

Then one can calculate the flow, pressure etc. of the concentrate, which is the feed to the second element. After calculating the results for all the elements, one may discover that the original feed pressure was too high or low, so the trial and error process starts with a new pressure.

With the help of the FILMTEC Reverse Osmosis System Anlysis computer program, accurate results can be obtained very quickly, so that this program can be used to modify and optimize the design of a system. Accordingly, the entire system calculation method will not be described here. It is also not intended to outline the process of the element to element computer calculation. However, the governing equations and parameters are given in Table 1.

In order to enable the determination of values for the terms A, ΔP, and $\Delta\pi$ in equation (1) the water permeation equation is expanded to equation (3). The permeate concentration can be derived from equation (2) after conversion into equation (12). The design equations are listed in Table 1, the symbol definitions in Table 3.

Entire System
This is a fairly easy method. Average values are used to calculate feed pressure and permeate quality if the feed quality, temperature, permeate flow rate, and number of elements is known. If instead of number of elements the feed pressure is specified, the number of elements can be calculated, with a few iterations. This method generally gives a result within 5% of that from element to element calculation. The design equations are listed in Table 2, the symbol definitions in Table 3.
Table 1: Design Equations for

Projecting RO System Performance

Individual Element Performance

Item	Equation	Ref.No.
Permeate Flow	$Q_i = A_i\,(\bar{\pi}_i) \times S_E \times TCF \times FF \times [P_{f_i} - \frac{\Delta P_{fc_i}}{2} - P_{p_i} - \bar{\pi}_i + \pi_{p_i}]$	(3)
Average Concentrate-Side Osmotic Pressure	$\bar{\pi}_i = \pi_{f_i} \times \frac{C_{fc_i}}{C_{f_i}} \times pf_i$	(4)
Average Permeate-Side Osmotic Pressure	$\pi_{p_i} = \pi_{f_i} \times [1 - R_i]$	(5)
Ratio: Arithmetic Average Concentrate-Side to Feed Concentration for Element i	$\frac{C_{fc_i}}{C_{f_i}} = [1 + \frac{C_{c_i}}{C_{f_i}}]\,/\,2$	(6)
Ratio: Concentrate to Feed Concentration for Element i	$\frac{C_{c_i}}{C_{f_i}} = [1 - Y_i\,(1 - R_i)]\,/\,[1 - Y_i]$	(7)
Feed Water Osmotic Pressure	$\pi_f = 1.12 \times [273 + T] \times \Sigma m_j$	(8)
Temperature Correction Factor for FT30 Membrane	$TCF = EXP\,[2640 \times \{1/298 - 1/(273 + T)\}];\ T \geq 25°C$ $= EXP\,[3480 \times \{1/298 - 1/(273 + T)\}];\ T \leq 25°C$	(9a) (9b)
Concentration Polarization Factor for FILMTEC® 8" elements	$pf_i = EXP\,[0.7 \times Y_i]$	(10)
System Recovery	$Y = 1 - \{(1 - Y_1) \times (1 - Y_2) \times \ldots (1 - Y_n)\} = 1 - \prod_{i=1}^{n} (1 - Y_i)$	(11)
Permeate Concentration	$C_{p_j} = B \times C_{fc_j} \times pf_i \times TCF \times \frac{S_E}{Q_i}$	(12)

Table 2: Design Equations for Projecting RO System Performance

System Average Performance

Item	Equation	Ref.No.
Total Permeate Flow	$Q = N_E x S_E x \bar{A}(\bar{\pi}) x TCF x FF x (P_f - \frac{\overline{\Delta P_{fc}}}{2} - P_p - \pi_f [\frac{\bar{C}_{fc}}{C_f} x pf - (\overline{1-}\bar{R})]\}$	(13)
Ratio: Average Concentrate-Side to Feed Concentration for System	$\frac{C_{fc}}{C_f} = \frac{-\bar{R} \times \ln[1 - Y/Y_L]}{Y - [1 - Y_L] \times \ln[1 - Y/Y_L]} + (1 - \bar{R})$	(14)
Limiting System Recovery	$Y_L = 1 - \frac{\pi_f \times \overline{pf} \times \bar{R}}{P_f - \overline{\Delta P}_{fc} - P_p}$	(15)
Approximate Log-Mean Concentrate-Side to Feed Concentration Ratio for System	$\left.\frac{\bar{C}_{fc}}{C_f}\right\rvert_{Y_L, \bar{R}=1} = -\frac{\ln[1 - Y]}{Y}$	(16)
Average Element Recovery	$\bar{Y}_i = 1 - [1 - Y]^{1/n}$	(17)
Average Polarization Factor	$\overline{pf} = EXP\ [0.7 x \bar{Y}_i]$	(18)
Average Concentrate-Side Osmotic Pressure for System	$\bar{\pi} = \pi_f x \frac{\bar{C}_{fc}}{C_f} x \overline{pf}$	(19)
Average Concentrate-Side System Pressure Drop for FILMTEC® 8" elements; 2 Arrays	$\overline{\Delta P}_{fc} = 0.04\, \bar{q}_{fc}^{\,2}$	(20a)
	$\overline{\Delta P}_{fc} = \left[\frac{0.1 \times Q/1440}{Y \times N_{V2}} x \{\frac{1}{N_{VR}} + 1 - Y\}\right]^2$	(20b)
Individual FILMTEC 8" Element, or Single-Array Concentrate-Side Pressure Drop	$\overline{\Delta P}_{fc} = 0.01 \text{ X } n \text{ x } \bar{q}_{fc}^{\,1.7}$	(20c)
FILMTEC Membrane Permeability as a Function of Average Concentrate-Side Osmotic Pressure	$\bar{A}(\bar{\pi}) = 0.125; \quad \bar{\pi} \leq 25$	(21a)
	$\bar{A}(\bar{\pi}) = 0.125 - 0.011 x [\bar{\pi} - 25] / 35; \quad 25 \leq \bar{\pi} \leq 200$	(21b)
	$\bar{A}(\bar{\pi}) = 0.070 - 0.0001 x [\bar{\pi} - 200]; \quad 200 \leq \bar{\pi} \leq 400$	(21c)
Permeate Concentration	$C_p = B x C_{fc} x \overline{pf} x TCF x \frac{N_E \times S_E}{Q}$	(22)

Table 3: Symbol Definitions

Q_i = Element i Permeate Flow (gallons/day, GPD)

$A_i(\overline{\pi}_i)$ = Membrane Permeability @ 25°C for Element i - a function of the average concentrate-side osmotic pressure (gallons/ft^2/day/PSI, GFD/PSI)

S_E = Membrane Surface Area per Element (ft^2)

TCF = Temperature Correction Factor for Membrane Permeability

FF = Membrane Fouling Factor

P_{f_i} = Element i Feed Pressure (PSI)

ΔP_{fc_i} = Concentrate-Side Pressure Drop for Element i (PSI)

P_{p_i} = Element i Permeate Pressure (PSI)

$\overline{\pi}_i$ = Element i Average Concentrate-Side Osmotic Pressure (PSI)

π_{f_i} = Element i Feed Osmotic Pressure

π_{p_i} = Element i Permeate-Side Osmotic Pressure (PSI)

pf_i = Concentration Polarization Factor for Element i

R_i = Salt Rejection Fraction for Element i (= [Feed Conc.–Perm Conc.] / [Feed Conc.])

C_{fc_i} = Average Concentrate-Side Concentration for Element i (ppm)

C_{f_i} = Feed Concentration for Element i (ppm)

C_{c_i} = Concentrate Concentration for Element i (ppm)

Y_i = Recovery Fraction for Element i (= Permeate Flow / Feed Flow)

π_f = Treated Feed Water Osmotic Pressure (PSI)

T = Feed Water Temperature (°C)

m_j = Molal Concentration of jth ion species

$\sum_j$ = Summation of All Ionic Species

Y = System Recovery (Expressed as a fraction) (= Permeate Flow / Feed Flow)

$\prod_{i=1}^{n}$ = Multiplication of n terms in a series

n = Number of Elements in Series

Q = System Permeate Flow (GPD)

N_E = Number of Elements in System

$\overline{Q_i}$ = Average Element Permeate Flow (GPD) = Q/N_E

$\overline{A}(\overline{\pi})$ = Average Membrane Permeability @ 25°C – a function of the average concentrate-side osmotic pressure (GFD/PSI)

$\overline{C}_{fc}$ = Average Concentrate-Side Concentration for System (ppm)

$\overline{R}$ = Average Fractional Salt Rejection for System

$\overline{\pi}$ = Average Concentrate-Side Osmotic Pressure for System (PSI)

$\overline{\Delta P}_{fc}$ = Average Concentrate-Side System Pressure Drop (PSI)

Y_L = Limiting (Maximum) System Recovery (expressed as a fraction)

$\overline{Y_i}$ = Average Element Recovery (expressed as a fraction)

$\overline{pf}$ = Average Concentrations Polarization Factor

$\overline{q}_{fc}$ = Arithmetic Average Concentrate-Side Flow Rate (GPM) (=[Feed Flow + Concentrate Flow] / 2)

N_V = Number of Six-Element Pressure Vessels in System; $\approx N_E / 6$

N_{V1} = Number of Pressure Vessels in First Array of 2-Array System; $\approx 2/3 \times N_V$

N_{V2} = Number of Pressure Vessels in Second Array of 2-Array System; $\approx N_V/3$

N_{VR} = Array Ratio = N_{V1}/N_{V2}

The subscript i in the equations of Table 1 indicates that they apply to the i^{th} element in a sequence of n elements in a series flow configuration. To accurately determine system performance, Equation 3 is successively solved for each of the n elements starting with an inlet set of conditions. The solutions depend on mass balances around each element for salt (Equation 7) and water (Equation 11), as well as correlations for individual element parameters such as concentrate-side flow resistance, ΔP_{fc} (Equation 20c); temperature correction factor for water permeability, TCF (Equation 9); polarization factor, pf_i (Equation 10) and the membrane permeability coefficient for water, $A_i(\pi_i)$ (Equation 21) which in the case of the FT30 membrane depends on the average concentrate concentration or, alternatively, osmotic pressure. These solutions usually involve a suitable average for the feed and permeate side hydraulic and osmotic pressures. For low recovery values typical of single element operation, an accurate solution can be obtained using a simple arithmetic average of the inlet and outlet conditions. Even so, since the outlet conditions are not known, iterative trial and error solutions are involved.

4.11.3
System Evaluation Computer Program

A FILMTEC® Reverse Osmosis System Analysis (ROSA) computer program is available to project the performance of given systems, and to optimize the design of the system. It can be further used for scaling calculations and to evaluate the performance of an existing system from its operating data.

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4.12 Testing

For the desalination of standard waters with a defined origin and composition, the RO system performance can be projected with sufficient accuracy by using the computer programme. In some cases, however, testing is recommended to support the proper system design. These include:

- Unknown feed water quality
- Unknown variation of feed water quality
- Special or new applications, e.g. process effluents and waste waters
- Special permeate quality requirements
- Extremely high system recoveries
- Very large plants

Testing is typically carried out at different subsequent levels:

4.12.1 Screening Test

The goal of a screening test is to select the right membrane and to obtain a rough idea about flux and rejection properties of this membrane. A small piece of flat sheet membrane is mounted in a "cell" and is exposed to the test solution using the cross-flow mechanism. The method is fast, inexpensive, and requires only small quantities of test solution. However, it does not provide engineering scale-up data, it cannot indicate long-term chemical effects of the solution on the membrane, nor does it provide data on fouling effects of the test solution.

4.12.2 Application Test

The application test provides scale-up data such as permeate flow and permeate quality as a function of feed pressure and system recovery. It typically involves the evaluation of a 50–100 liter (15–30 gallons) sample of solution on a 2540-sized membrane element. The element is mounted in a test machine with the engineering features of production systems. The feed flow and feed pressure can be varied in the range of the element's operation limits.

In a first test series, both concentrate and permeate are recycled back to the feed tank. Permeate flow and permeate quality are the feed pressure at which the desired permeate flow (typically 80 l/h per 2540-element) is obtained, is then fixed for the second test series.

The second series is run in the batch mode, leading the permeate into an extra containment and returning the concentrate to the feed tank. Both permeate flow and permeate quality are monitored during the factor. The concentration factor CF is the ratio of the actual feed volume to the original feed volume. The test is stopped when the permeate flow has declined to an uneconomically low value, e.g. 20 l/h (0,09 gpm) for a 2540-sized element.

By repeating the batch tests, an indication of membrane stability and fouling effects can be provided. Long-term performance including the assessment of cleaning procedures, however, can only be obtained by pilot tests.

4.12.3 Pilot Tests

A pilot test is run in the field, typically on a representative fraction of the feedstream, in a continous operation mode. The pilot plant has at least one production-size element, preferably an arrangement of elements similar to the arrangement in a large-scale system. The permeate flow of the pilot plant should be at least 1% of the large-scale plant flow, and should be run for a minimum of 30 days. The objective is to confirm the system design and to fine-tune operating parameters as well as to minimise the risk in large projects.

4.13 System Components

4.13.1
High Pressure Pump

The pump discharge pressure has to be controlled to maintain the designed permeate flow and to not exceed the maximum allowed feed pressure, which is:

21 bar	for TW30 Elements
41 bar	for BW30 Elements
69 bar	for SW30 and SW30HR Elements

A positive displacement pump cannot be throttled, so pressure is controlled by a back pressure valve installed in a bypass line from the pump discharge to the pump suction. A pulsation damper (accumulator) on the pump discharge line is used to minimize pressure pulsations. A relief valve ensures that the maximum allowed pressure cannot be exceeded.

A centrifugal pump is controlled by a throttling valve on the discharge line. A variable speed motor is an energy saving, but also more expensive, alternative.

In sea water systems, typically, 55-60% of the pressurized feed water leaves the system with about 60 bar pressure in the concentrate stream. This energy can be recovered in order to decrease the specific energy demand of the system. Energy recovery methods are:

- Pelton wheel
- Reverse turning turbine
- Piston type work exchanger

The high pressure concentrate is fed into the energy recovery device where it produces a rotating power output. This is used to assist the main electric motor in driving the high pressure pump. Compared to traditional pump drives the energy recovery system represents energy savings up to 40%.

4.13.2
Pressure Vessel

Pressure vessels are available with different diameters, lengths, and pressure ratings. PV-1512/1812 is supplied by Payne, all other vessels by Advanced Structures Inc. (ASI). Table 1 gives a summary of all vessels.

Table 1: Pressure Vessels

Vessel	Pressure Rating (PSI)
1 .5" and 2.5" diameter pressure vessels	
PV-1512-1	85
PV-1812-1	85
PVS-2514-1	1,000
PVS-2521-1	1,000
PVS-2521-2	1,000
PVS-2540-1	1,000
PVS-2540-2	1,000
Coupler Kit	
4" diameter pressure vessels	
PVB-4014-1	600
PVB-4021-1	600
PVB-4040-1	600
PVB-4040-2	600
PVB-4040-3	600
PVB-4040-4	600
PVB-4040-6	600
PVU-4021-1	1,000
PVU-4040-1	1,000
PVU-4040-2	1,000
PVU-4040-3	1,000
PVU-4040-4	1,000
PVU-4040-6	1,000
Coupler Kit	
8" diameter pressure vessels	
PVE-8040-1	400
PVE-8040-2	400
PVE-8040-3	400
PVE-8040-4	400
PVE-8040-6	400
PVE-8040-7	400
PVE-8040-1	600
PVE-8040-2	600
PVE-8040-3	600
PVE-8040-4	600
PVE-8040-6	600
PVE-8040-7	600
PVE-8040-1	1,000
PVE-8040-2	1,000
PVE-8040-3	1,000
PVE-8040-4	1,000
PVE-8040-6	1,000
PVE-8040-7	1,000
Coupler Kit	400/600
Coupler Kit	1,000

The chosen pressure rating must be high enough to allow some pressure increase to compensate for irreversible fouling (typically 10% more than needed in a 3-year-design).

When dynamic permeate backpressure is employed during plant operation, the limiting component is the permeate port which is made of PVC. The permeate pressure rating is a strong function of temperature, as shown in Table 2. Note that at static conditions, i.e. with the high pressure pump shut down, the permeate back pressure must never exceed 0.3 bar (5 PSI).

For pressure vessel descriptions and installation recommendations refer to Section 6.

4.13.3
Shutdown Switches

The membrane elements have to be protected against undue operating conditions.

If ever there is a possibility that such conditions can occur, for example by a pretreatment upset, provisions must be made so that the system is shut down in this case of emergency.

Some undue operating conditions and the provisions to prevent these are listed in Table 3.

Table 2: Maximum Dynamic Permeate Backpressure for FILMTEC® Pressure Vessels

Temperature (°C)	Temperature (°F)	Maximum Dynamic Permeate Back Pressure (bar)	Maximum Dynamic Permeate Back Pressure (PSI)
45	113	10.0	145
40	104	12.4	180
35	95	15.1	219
30	86	17.7	257
25	77	20.6	299
20	68	23.3	338

Table 3: Provisions Against Undue Operating Conditions

Undue Operating Condition	Provision
Too high feed pressure	High pressure shutdown switch in the feed line
Insufficient feed pressure the pump suction line	Low pressure shutdown switch in
Too high feed temperature	High temperature switch in the feed line
Permeate pressure exceeding feed by more than 0.3 bar	Pressure relief mechanism in the pressure permeate line
Too high concentration of colloidal matter in the feed	Turbidity control in the feed line
Too high concentration of sparingly soluble salts in the feed	Dosing pumps for acid and antiscalant should be electrically interlocked with the RO pump drive High pH shutdown switch
Oxidizing agents in the feed	ORP control in feed line or chlorine detection monitor with automatic shutdown
Oil in the feed	Oil detector in feed line

4.13.4 Valves

Following valves are typically included in an RO system:

- Feed inlet valve to shut down the plant for maintenance and preservation.
- Valve on the pump discharge line or pump bypass line to control feed pressure during operation and feed pressure increase rate during start-up.
- Check valve on pump discharge line.
- Check valve and atmospheric drain valve on permeate line to prevent the permeate pressure from exceeding the feed pressure.
- Flow control valve on the concentrate line to set the recovery. (Caution: back-pressure valve must not be used).
- Valve in the permeate line to provide permeate drain during cleaning and start-up.
- Valves in the feed and concentrate line (and between arrays) to connect a cleaning circuit.

4.13.5 Control Instruments

To ensure proper operation of the RO system, a number of control instruments are necessary. The accuracy of all instruments is critical. They must be installed and calibrated according to manufacturers' instructions.

- Pressure gauges to measure the pressure drop across the cartridge filter, the pressure on the pump inlet line and discharge line, the feed pressure to the membrane element(s), the pressure drop between feed and concentrate of each array, and eventually the pressure in the permeate line. Liquid-filled gauges should contain membrane compatible fluids such as water or glycerine in place of oils or other water immiscible liquids.
- Flow meters to measure concentrate and total permeate flow rate, also permeate flow rate of each array.
- Water meters in the permeate and feed line to log the total water volume treated and produced.
- Hour meter to log the total operating time.
- pH meter in the feed line after acidification to control carbonate scaling potential.
- Conductivity meters in the feed line, in the brine line, and in the permeate line to determine permeate quality and salt rejection.
- Sample ports on the feed, concentrate and permeate line (total permeate and permeate of each array) to be able to evaluate system performance. A sample port on each pressure vessel permeate outlet is recommended to facilitate troubleshooting.

4.13.6 Tanks

Storing water in tanks should be generally kept at a minimum. When tanks are used, the inlet and outlet should be placed so that no stagnant zones are permitted. The tanks should be protected from dust and microbiological contamination. In critical applications tanks are closed and vented through a HEMA-filter.

A **feed tank** is needed to provide the reaction time (20-30 min.) when chlorine is used. The free volume of media filters can be used for this purpose as well. Feed tanks are also frequently used as a buffer to allow continous operation of the RO section (e.g. during backwash of filters). Systems that are operated in the batch or semi-batch mode require a feed tank.

A **permeate tank** is typically employed, when the permeate is the product. Plant start-ups and shut-downs are initiated by low-level and high-level signals from the permeate tank. The system capacity and the tank size should be designed so that the RO plant is allowed to run for some hours continuously. The less frequently the plant is shut down, the better is the system performance.

A **draw-back tank** is a small tank in the permeate line that provides enough volume for natural osmosis backflow when the system shuts down. It is typically employed in sea water systems, but not in brackish water systems. A missing draw-back tank can cause air to be sucked into the FILMTEC® elements. This may create the following problems:

- ➔ Contamination of the permeate side of the membrane by airborne microbes and fungii.
- ➔ Hydraulic shocks and slugs of air upsetting meters and set point controllers when the air is expelled from the system on the next start-up.
- ➔ Drying of the membrane (flux loss).
- ➔ If the feedwater is in a reduced status and contains H_2S, Fe^{2+}, Mn^{2+}, etc., the air intrusion may cause fouling of the membrane by oxidized and precipitated colloidal matter.

If the product water from an RO system is chlorinated, care must be exercised to ensure that the chlorine does not migrate back to the membrane. Air breaks should be employed appropriately.

If a draw-back tank is used, its water level should be higher than the highest pressure vessel, but not exceeding 3m from the lowest vessel. To prevent contamination, the flow is in at the bottom and out the top, and the tank must be covered. Post-chlorination if performed must be done downstream of this tank.

The volume of the draw-back tank can be sized as follows:

$$V_{DBT} = 25\ N_E - V_{PP}$$

V_{DBT}: Volume of draw-back tank (in liter)

N_E: Number of installed element

V_{PP}: Volume of permeate piping between pressure vessels and draw-back tank (in liter)

Dosing tanks are required when chemicals are added to the feed water. They should be sized typically for a daily refillment.

A cleaning tank is part of the cleaning equipment as described in Section 7.

4.13.7
Optional Equipment

Various optional equipment and features are useful in operating and monitoring the system:

- A shut-down flush system flushes the feed-concentrate line with pretreated feed water or with permeate after shut-down. When antiscalants are used, a flush system is mandatory.
- Alarms for
  - high permeate conductivity
  - high concentrate conductivity
  - low feed pH
  - high feed pH
  - high feed hardness
  - high feed temperature
  - low level in dosing tank
- Continuous recorder for
  - feed temperature
  - feed pH
  - feed and permeate conductivity
  - feed SDI
  - feed ORP
  - feed, permeate and concentrate pressure
  - permeate and concentrate flow

  Ideally, a monitoring system is installed that allows on-line recording and processing of all important operating data of the system (see also Section 6.4, Record Keeping).
- Control and motor starter panel with automatics ensuring a safe plant operation. Automatics for filter backwash, membrane cleanings and plant flush outs can be incorporated.
- Compressed air system including compressor, air dryer, air control stations and complete pipe systems.
- Spare parts for 1 or 2 years of operation.
- Tools for general and special services.
- Options such as training, supervision and maintenance.

4.14 Materials of Construction, Corrosion Control

From a corrosion point of view a very harsh environment prevails in an RO water desalination plant.

Hence the materials of construction must possess a certain degree of corrosion resistance. This counts for both the exterior parts exposed to spillage and a humid and saline atmosphere as well as for the interior of the system exposed to the wide variety of waters treated.

Although not to be underestimated, the control of the exterior corrosion can usually be overcome by using a surface coating (painting, galvanizing, etc.) on materials supposed to corrode (mild steel, cast iron, etc.) and by establishing a maintenance program involving periodical flush down and cleaning, repair of leaks, etc.

Selecting materials of construction for the interior wetted system is a far more complicated task.

Apart from being compatible with the pressures, vibrations, temperatures, etc. existing in an RO system, the materials used must also be able to withstand the potential corrosion attacks caused by the high chloride content of the feed water and the concentrate stream, the aggressive product water and the chemicals used for applications such as membrane cleaning.

Application of non-metallic materials such as plastics, fiberglass, etc. are widely used for preventing corrosion and chemical attacks as well in the low-pressure (< 10 bar) part of the RO system as in the RO elements and pressure vessels.

However, it is usually necessary to use metals for the high-pressure (10-70 bar/200-1,000 PSI) parts such as pumps, piping and valves. Carbon and low alloy steels do not have sufficient corrosion resistance, and their corrosion products can foul the membranes.

Lined piping is usually not a realistic alternative because of the often compact piping design and relatively great amount of connections and fittings needed.

Al-bronze can be an alternative for pumps etc., but the risk of erosion corrosion and chemical attacks must be taken into account.
The most relevant material to be used for the high-pressure parts is **stainless steel.**

The basic advantages with stainless steel are that they are very resistant to general corrosion and erosion corrosion. Stainless steel is rarely attacked by galvanic corrosion, but it will influence the attack on the other metal in a two-metal couple (e.g. copper, brass, etc.). Stress corrosion cracking of stainless steels in media containing chloride rarely occurs below 70°C (158°F) so it does not need to be considered in an RO desalination plant.

Unfortunately, some stainless steels are prone to pitting and crevice corrosion in the waters occurring in an RO plant.

Pitting means localized attacks that result in holes in the metal. Pitting occurs where the passive film formed by chromium oxides breaks and chlorides can attack the bare metal. Crevice corrosion is pitting associated with small volumes of stagnant water caused by holes, gasket surfaces, deposits and crevices under bolts, etc.

In order to avoid pitting and crevice corrosion in the RO water desalination plant the following recommendations can be given:

RO Plants with Concentrate Stream TDS below 7,000 ppm:

Stainless steel type AISI 316 L with <0.03% C is the minimum demand for the pipe system, as lower grade stainless steels with higher carbon content will suffer from pitting in the welding zones (intergranular corrosion).

For non-welded parts stainless steel type AISI 316 is usually acceptable.

RO Plants with Concentrate Stream TDS higher than 7,000 ppm:

Stainless steel type 904 L is recommended for pipes and bends for welding and for similar parts without crevices.

Where crevices occur, such as at flange connections, in valves, in pumps, etc. stainless steel type 254 SMO or alike with ≥ 6% Mo is recommended.

These two higher alloy stainless steels can be welded together without risking galvanic corrosion.

Sensor element of instruments may be coated or lined.

Table 1: Composition of Stainless Steels:

Usual Designation	UNS No.	C%	Cr%	Ni%	Mo%	Cu%	N%
AISI 316	S 31600	< 0.08	16.0-18.0	10-14	2.0-3.0	-	-
AISI 316L	S 31603	< 0.03	16.0-18.0	10-14	2.0-3.0	-	-
904 L	N 08904	< 0.02	19.0-23.0	23.0-28.0	4.0-5.0	1.0-2.0	-
254 SMO	S 31254	< 0.02	19.5-20.5	17.5-18.5	6.0-6.5	0.5-1.0	0.18-0.22

The composition of the named stainless steels is given in Table 1.

Besides the above recommendations general precautions must be taken during design and construction, such as:

- Design with a minimum of crevices and dead ends.
- Design the piping so that the flow velocity is above 1.5 m/s (5 ft/s). It promotes the forming and maintenance of the passive film.
- Use backing gas when welding in order to avoid the weld oxide film forming base for crevice corrosion.
- Pickle and passivate the pipe system as this gives the optimum safety against chloride attack.
- Flush the plant with low TDS water before a shut-down period.

5. Assembly and Loading of Pressure Vessels

5.1 Preparation

Load FILMTEC® elements into the pressure vessels just prior to start-up. Before assembling all components, check the parts list and make sure all items are present in the right quantities. Carefully remove all dust, dirt and foreign matter. Clean the pressure vessel on the inside and check visually. If necessary, provide scrubbing action with an improvised swab. If necessary, flush or wash the feedwater piping system and RO vessels with a chemical solution before installing membrane elements. This will assure that all foreign matter has been removed. Before installing the elements, let the feedwater run through the vessels for at least 30 minutes and check feedwater quality to be according to specifications. Lubricate the inside using a clean cloth soaked in glycerine. Lubricate all O-rings prior to assembly with glycerine. When O-rings are installed, expand them slightly – do not roll them into position.

When pressure vessels are reassembled, make sure that the parts of one vessel are not mixed with parts of other vessels.

Prepare a schematic diagram of the RO system for recording pressure vessel and element locations. It should show the piping of the whole rack. For location recording use the FILMTEC element serial number written on the label of each element. Use this diagram to always keep track of each individual element in your system.

Check that the pressure vessel is solidly secured to the racks.

Following material is recommended to load pressure vessels (for example, 8-inch-6-element PV's):

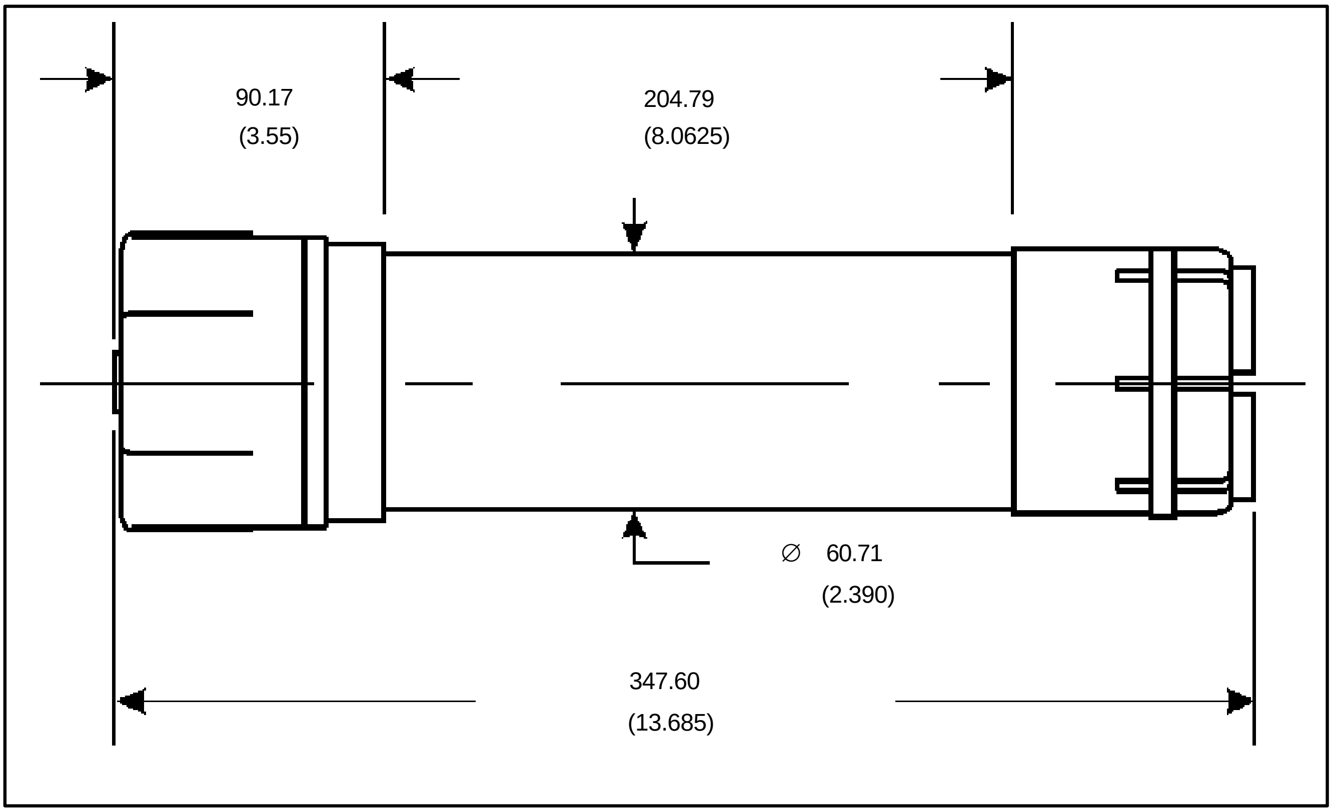
- Clean cloth material
- PVC plastic pipe (5 m long, 50-60 mm outer diameter)
- Glycerine (2-3 liters)
- Flashlight
- Rubber boots
- Safety gloves or rubber/plastic gloves
- Cord (rope) 20 m
- 10 m tape measure (~ 30 feet)
- 3 pails of 20 l each
- Work table (2 m x 1 m)
- 10 boxes of about 300 x 300 mm or larger (board material) to sort parts
- 10 rolls of paper tissue
- Rubber hammer / cushioned mallet or hammer and wood block
- Snap ring pliers
- Adhesive tape
- Allen wrench

For conversion into U.S. units, see Section 10.7.

5.2 PAYNE PV-1512/1812 Pressure Vessel

This pressure vessel (P/N 81247) houses one FILMTEC® element TW30-1512 or TW30-1812. It consists of 3 parts: vessel tube, endcap, and O-ring. Before inserting the element, inspect for binding threads.

Material:	PVC
Pressure rating:	6 bar (85 PSI)



Notes:
1. All dimensions are reference dimensions in mm (inch).
2. All ports are 1/8" NPT.

5.3 A.S.I. PVS-2.5-1000 Pressure Vessel

Assembly Instructions

Opening the Vessel

Read precautions.

Relieve pressure from vessel.

A. Disconnect vessel from system at nearest convenient location (other than plumbing on vessel fittings). Be careful not to remove anodise treatment from aluminium.

B. Cut lockwire **9** which secures sockethead screws **7.** Remove and discard wire.

C. Remove two sockethead screws **7** and washers **8.**

D. Using a wooden dowel and rubber mallet, tap in end plug **2** far enough to clear locking ring groove.
CAUTION: Do not tap on fittings; this could damage head ports.

E. Pry locking rings **6** out of groove and remove. If necessary, use a pointed object, such as an icepick, to pry rings out.

F. Pull out end plug **2.**

G. Remove fittings.

H. Remove and discard internal and external O-rings **5, 4.**

I. Refurbish components as required, following the instructions below.

    a. Use a wire brush or suitable abrasive to remove all encrusted salts, corrosion by-products and other deposits from locking rings **6,** washers **8** and locking ring groove in shell **1.**

    b. Rinse parts in fresh water to remove any particles that might foul membrane element.

    c. Replace parts that cannot be restored to as-new condition, including O-rings **4, 5.**

Remaking the Piping Connections

A. Use a wire brush or suitable abrasive to remove all encrusted salts, corrosion by-products and other deposits from pipe threads.

B. Rinse parts in fresh water.

C. Apply sealant on male threads and assemble joint(s).

Closing the Vessel

Single Element Assembly

Installing the end plug.

A. Apply glycerine to shell chamfer and walls about ½ inch from chamfer. Wear protective gloves or finger cots to prevent cuts or penetration by glass fiber particles.

B. Install O-ring **5** into internal O-ring groove on end plug **2.**

Parts Description
A.S.I. PVS-2.5-100 Pressure Vessel

Item	Qty Required	Description
1	1	Shell
2	2	End Plug
3	2	Bearing Plate
4	2	External O-Ring (2-227)
5	2	Internal O-Ring (2-116)
6	2	Locking Ring Set
7	4	Sockethead Screw
8	4	Alignment Washer
9	2	Lockwire
10	One less than number of Elements	Coupler
11	2 per Coupler	Coupler O-Ring (2-210)

Pressure Vessel Complete is available in sizes to house one or two FILMTEC® elements.

[1] Not sold separately

C. Install O-ring **4** on external O-ring groove on end plug **2.** Lubricate both O-rings lightly with glycerine.

D. Place bearing plate **3** on end plug **2** at end of plug opposite O-rings **4, 5.** Spot-faced holes for washers **8** must face out. Align holes in bearing plate with threaded ports in end plug.

E. Apply thread sealant on fittings (not provided) and install fittings through bearing plate **3** into end plug **2.** Turn fitting 1/2 turn past hand tight. Do not overtighten; this could crack end plug.

F. Orient fittings in desired position and insert end plug **2** into shell **1.** Using both thumbs, apply equal pressure on opposite sides of end plug to force it into shell until top of bearing plate **3** clears groove for locking rings **6** inside diameter of shell.

G. Adjust fitting orientation as desired.

H. Insert locking rings **6** with stepped face out. Position two locking rings so two spot-faced holes are aligned in gap between rings. When vessel is in horizontal position, it may be easier to install bottom locking ring first, then top locking ring, which must be held in place until end plug **2** is pulled out (step 1).
CAUTION: Stepped face of locking rings **6** must be facing out (see detail) to insure a proper interlock when assembly is completed.

I. Using fittings, pull out end plug **2** slightly to retain locking rings **6** in place.

J. Install one washer **8.** Slide edge of flat washer into locking ring groove until washer is fully seated in its spot-faced hole. Verify that washer is correctly seated, then secure it with a sockethead screw **7.**
CAUTION: Washers **8** must be installed exactly as described in step J to insure safe interlock and retention of end plug **2**.

K. Repeat step J to install opposite washer **8.** Tighten sockethead screws **7** until washers are snug against bearing plate **3.**

L. Secure assembly with lockwire **9** threaded through holes in sockethead screw **7** head and looped around fittings, (see detail). This is reject end of vessel.
CAUTION: Lockwire **9** must be installed to insure integrity of critical interlock. If stainless steel lockwire is not available, any steel wire of .020 gauge may be used.

M. Lubricate element U-cup seal with glycerine.

N. Insert element into open end of shell **1** (feed end) with U-cup seal flaring toward feed end of shell.

O. Install feed end plug assembly using steps A through L. Product water (center) tube of element will fit into hub of end plug **2.**

Double Element Assembly

A. Follow steps A through N. For a single Element Assembly.

B. Install O-rings **11** into coupler **10.** Lubricate lightly with glycerine.

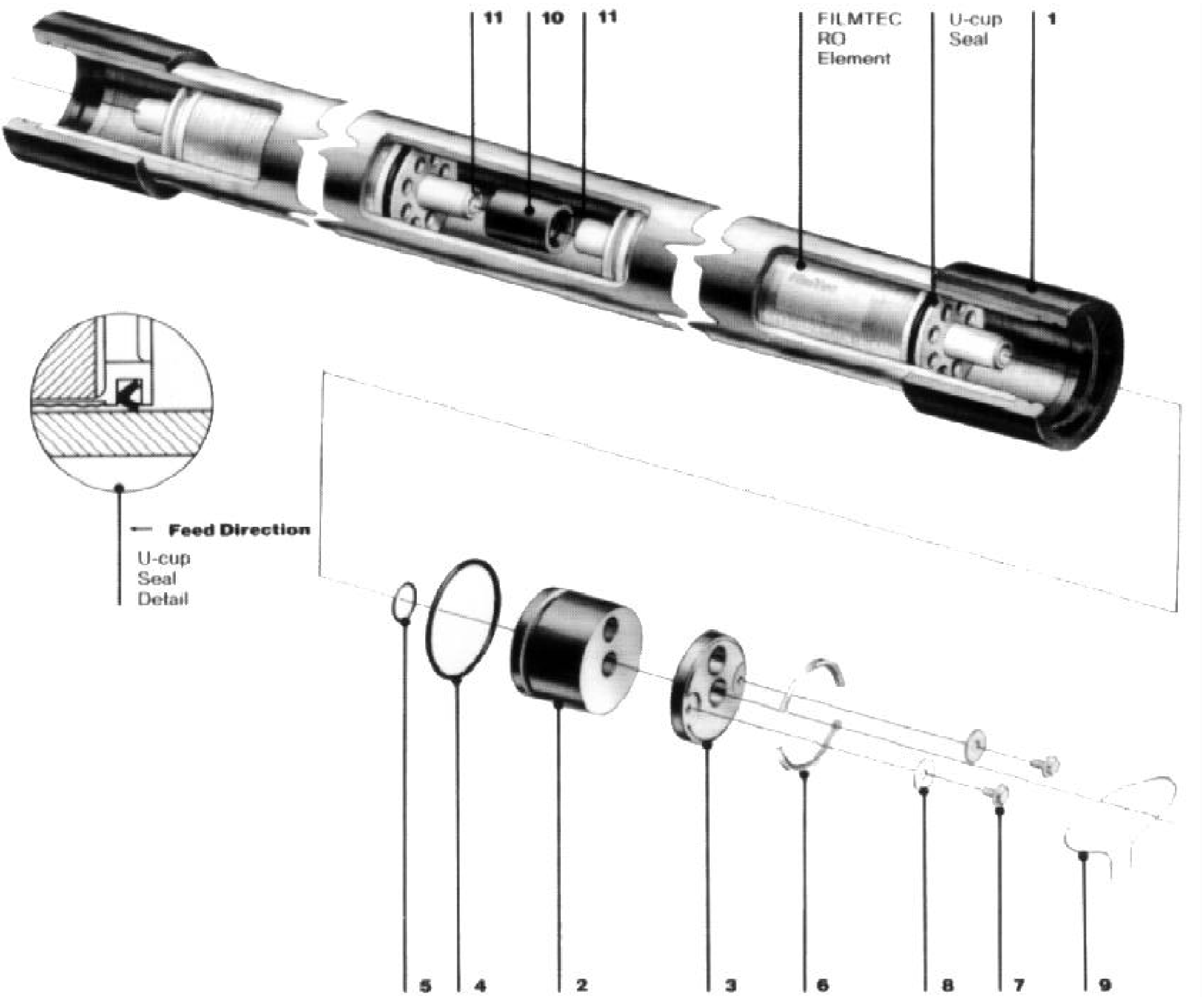
C. Insert product water (center) tube of first element into one end of coupler **10.** Coupler should touch white plastic end cap of element.

D. Repeat step M for second element.

E. Insuring that U-cup seal flares toward feed end of shell **1,** insert product water (center) tube of second element into remaining end of coupler **10.**

F. Insert second element into shell **1** as far as possible.

G. Follow step O.


11
10
11
FILMTEC RO Element
U-cup Seal
1
← Feed Direction
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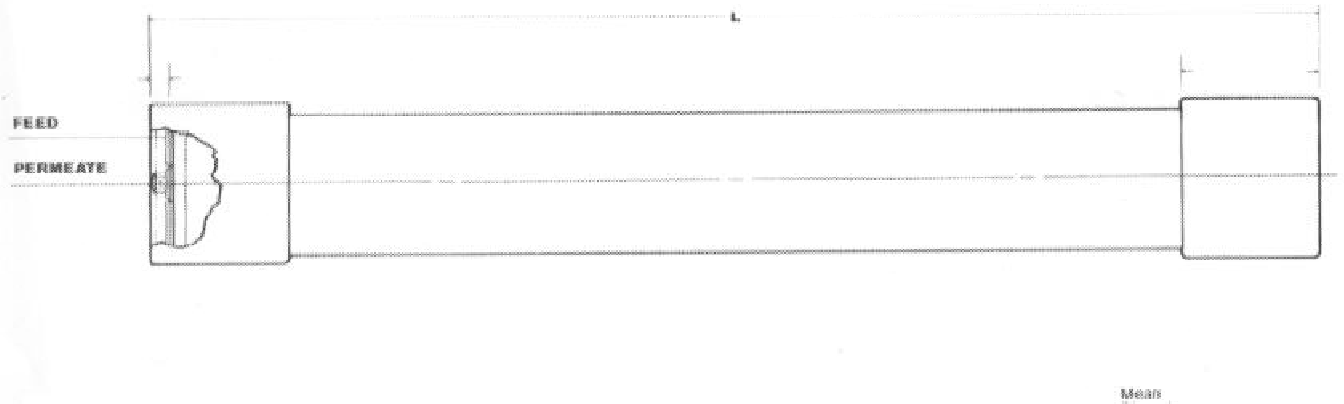
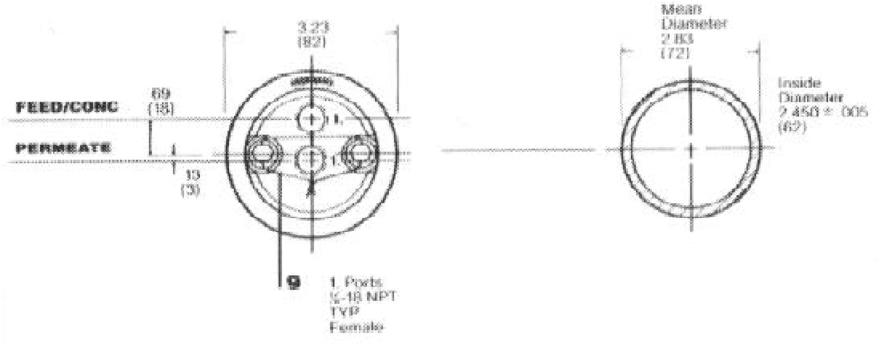




Dimensions expressed as
inch (millimeter)

Precautions

Read and follow instructions. Failure to take every precaution will void manufacturer's warranty and may result in vessel failure. The A.S.I. PVS-2.5-1000 pressure vessel must be installed and maintained in accordance with the precautions listed and good industrial practice to assure safe operation over a long service life. The high performance FRP shell must be allowed to expand under pressure; undue restraint at support points or piping connections can cause leaks to develop in the shell. The end closure, incorporating close-fitting, interlocking metal components, must be kept dry and free of corrosion; deterioration can lead to catastrophic mechanical failure of the end plug.

Do not make rigid piping connections to ports or clamp vessel to restrict expansion of shell under pressure.

Do not hang piping manifolds from ports or use vessel to support other components.

Do not operate vessel in excess of its design pressure and operating temperature range.

Do provide overpressure protection for vessel, set at not more than 105 % of design pressure.

Do not tolerate leaks or allow end closures to be routinely wetted in any way.

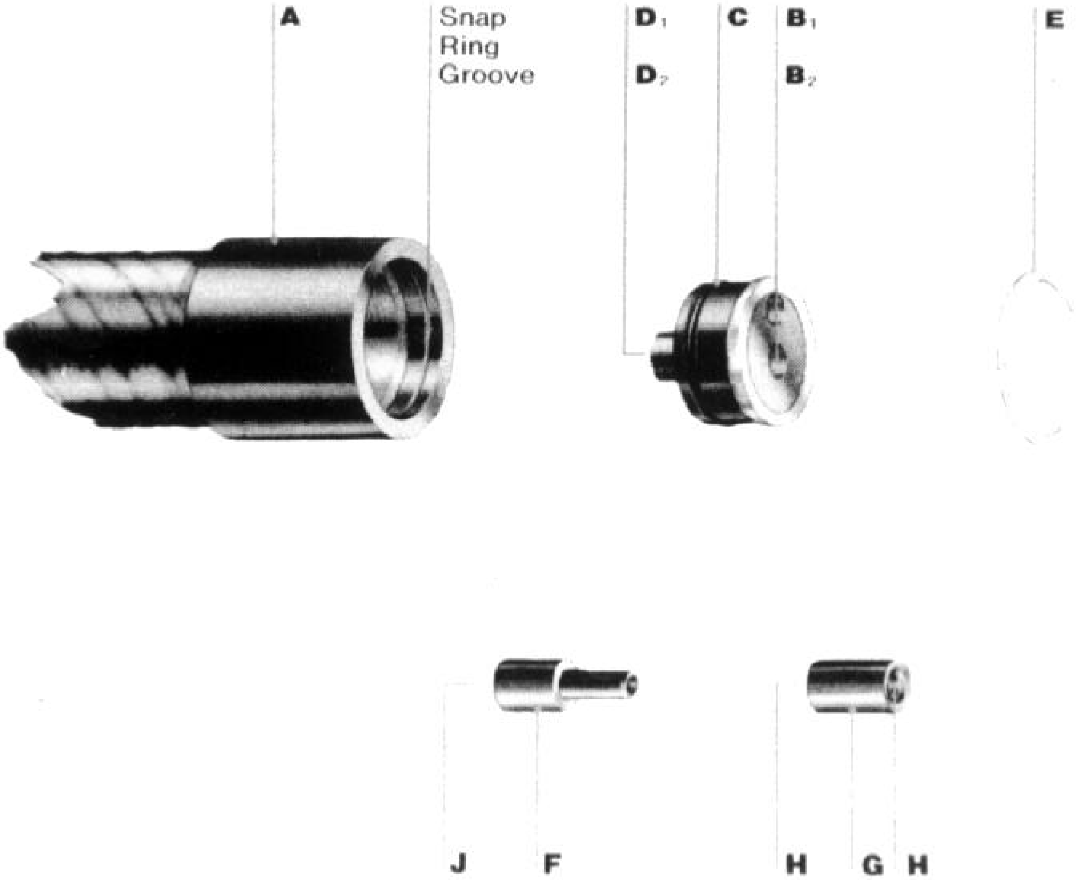
Do not pressurize vessel until verifying the locking ring set is fully seated and secured by screws and safety wire.

Do not work on any component before verifying pressure is relieved from the vessel.

Length and Assembly Weight

Size	L ± .03		Empty Wt. (approx.)	
	mm	(In)	kg	(Lb)
PVS-2514-1	444	(17.5)	2.3	(5)
PVS-2521-1	622	(24.5)	3.2	(7)
PVS-2521-2	1,156	(45.5)	4.1	(9)
PVS-2540-1	1,105	(43.5)	4.1	(9)
PVS-2540-2	2,121	(83.5)	5.4	(12)

5.4 A.S.I. PVB-4-600 Pressure Vessel



Single Element Assembly

1. Install O-rings (C, D_1) on each end plug (B_1). Lubricate lightly with glycerine.
2. Insert end plug (B_1) into one end of the vessel (A) until it is slightly past snap ring groove.
3. Install snap ring (E) making sure it is fully seated in snap ring groove. This is reject end of vessel.
4. Lubricate element u-cup brine seal with glycerine.
5. Insert element into other end of vessel (feed end) making sure u-cup brine seal flares toward feed end of vessel.
6. Install feed end plug assembly using steps 1-3.

Multiple Element Assembly

7. Follow steps 1-3 using end plug B_2 and D_2.
8. Insert O-ring (J) into adaptor (F). Lubricate lightly with glycerine.
9. Place one adaptor (F) on product water tube of first element opposite the end with the brine seal.
10. Insert O-rings (H) into coupler (G). Lubricate lightly with glycerine.
11. Follow steps 4-5 using coupler (G) to join elements as they are being inserted into vessel.
12. Place second adaptor on product water tube on brine seal end of last element.
13. Follow step 6 using end plug B_2.

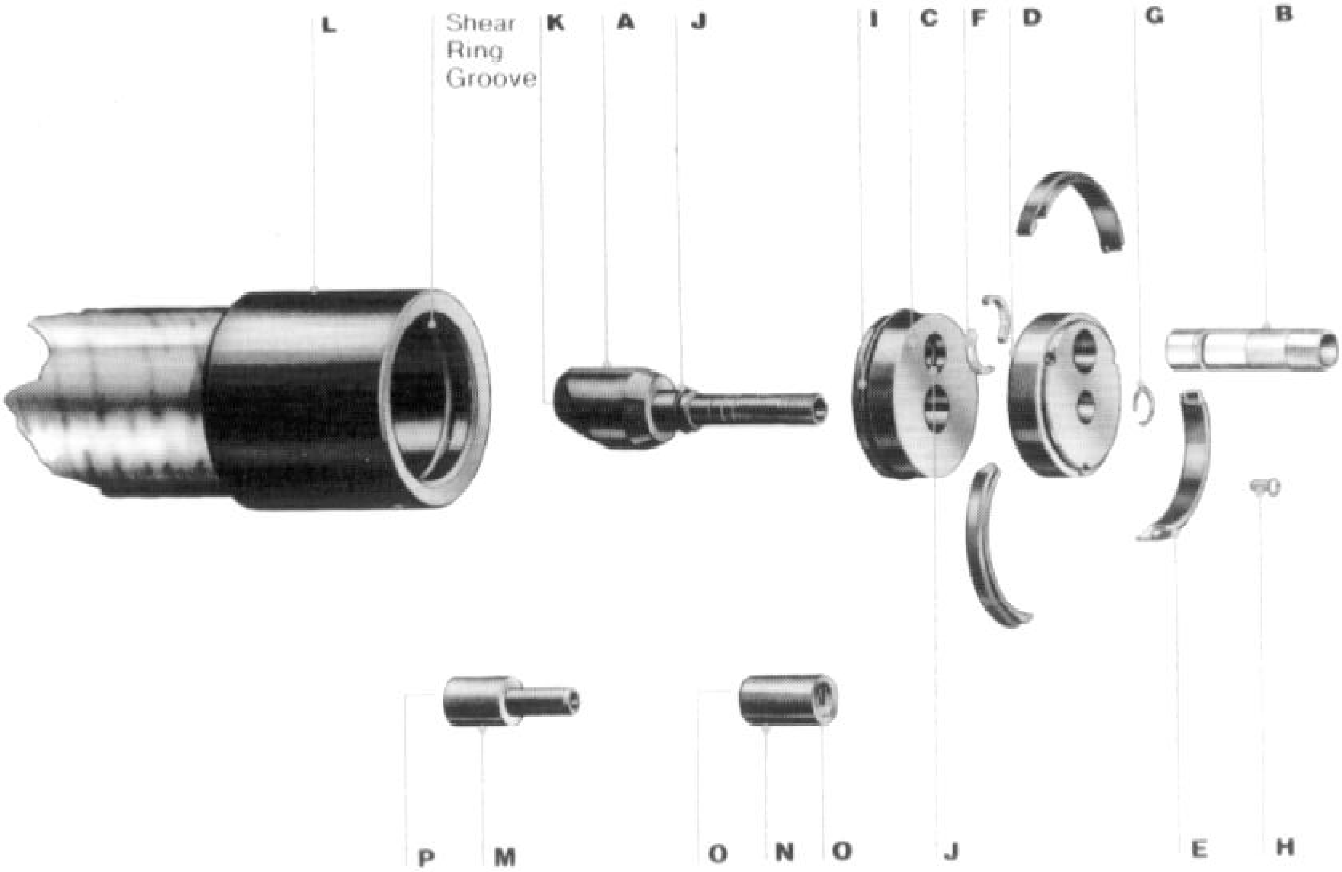
Single Element Vessel Parts List
A.S.I. PVB-4-600

Item	Quantity per Vessel	Description
A	1	4021-1 Vessel Tube 4040-1 Vessel Tube
B_1	2	4" End Plug
C	2	O-Ring
D_1	2	O-Ring
E	2	4" Snap Ring

Multiple Element Vessel Parts List

A	1	4040-2 Vessel Tube 4040-3 Vessel Tube 4040-4 Vessel Tube 4040-6 Vessel Tube
B_2	2	4" End Plug
C	2	O-Ring
D_2	2	O-Ring
E	2	4" Snap Ring
F	2	Adaptor
G	One less than number of Elements	External Coupler
H	2 per Coupler	O-Ring
J	2	O-Ring

5.5 A.S.I. PVU-4-1000 Pressure Vessel



End Plug Assembly

The assembly of the complete 4" “End Plug Kit” (Picture 1) is carried out in the following way:

a. Place all items (Picture 2) in a clean place and ensure that all O-rings etc. are in good condition. Otherwise change them.

b. Mount the pressure port (B) in the bearing plate (D), push it forward until the segmented retaining ring (F) can be mounted (Picture 3) and pull the pipe back again until the rings are flush with the surface (Picture 4).

c. Mount the O-rings in the hub (inside and outside) (Picture 5) in the plug plate (inside and outside) (Picture 6), and in the adaptor, if more than 1 element (Picture 7).

d. The adaptor (Picture 7) is only used in vessels with more than 1 element.

e. Connect the adaptor and the hub (Picture 8) and mount these in the plug plate (Picture 9).

f. Now the complete End plug kit can be put together (Picture 9).

g. To keep the parts together you mount the snap ring in the groove of the hub (Picture 1).

You are now ready to start the element mounting in the pressure vessel.

NB: Normally it is easier to grease the O-rings before assembly, but for this purpose never use any kind of silicone products as this will ruin the membranes (extremely low fluxes).

Vessel Assembly

1. Insert assembled end plug into either end of vessel (L) about ¼ inch past shear ring groove inside vessel.
2. Insert segmented shear ring (E) into groove so spaces between segments are aligned with holes in bearing place. Install three end plug screws (H) and tighten completely. This is reject end of vessel.
3. Insert element into the other end of vessel.
4. Install feed end plug assembly in the same manner as reject end plug and secure end plug screws.
5. For multiple element vessels, follow same assembly procedure except a slightly different hub (A) is used with adaptor (M) on both ends of vessel. Element product water tubes are joined with external coupler (N) as elements are inserted into vessel.

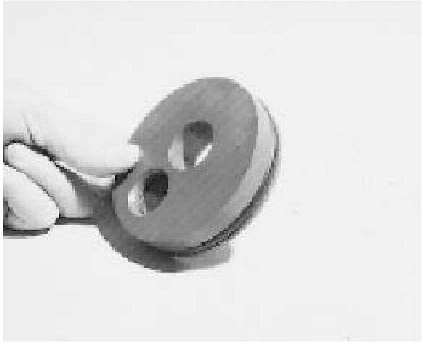
Picture 1

Picture 2

Picture 3

Picture 4

Picture 5



Picture 6

Picture 7

Picture 8

Picture 9

Single Element Vessel Parts List

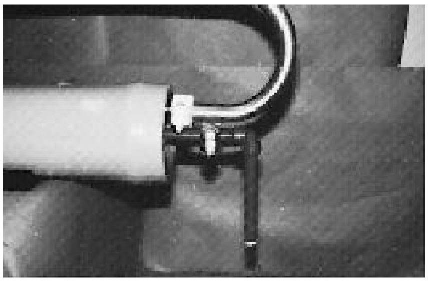
A.S.I. PVV-4-1000

Item	Quantity per Vessel	Description
A	2	Hub
B	2	Port
C	2	Plug Plate
D	2	Bearing Plate
E	2	Segmented Shear Ring
F	2	Segmented Retaining Ring
G	2	Snap Ring
H	6	End Plug Screw
I	2	Plug Seal
J	4	Port-Hub Seal
K	2	PWT Seal
Q	2	End Plug Kit contains A through K

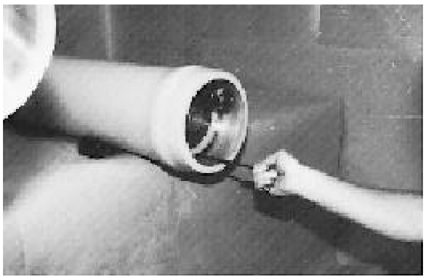
Multiple Element Vessel Parts List

A	2	Hub
B-J		Same as Single Element Vessel
K	2	Adaptor Seal
M	2	Adaptor
N	One less than number of Elements	Coupler
O	2 per Coupler	O-Ring
P	2	PWT Seal
R	2	End Plug Kit contains A through K
S	2	Strap
T	2	Pad

[1] not shown

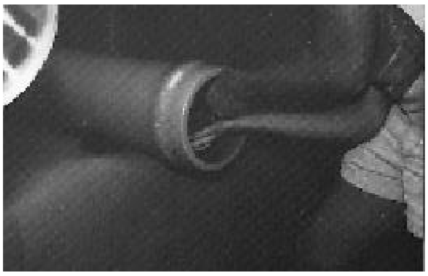


Picture 1: Disconnecting Ports



Picture 2: Securing Screw 12 Removal

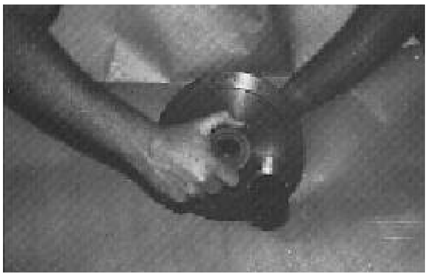
Picture 3: Key Segment Removal



Picture 4: End Plug Removal

Picture 5: Installing Thrust Ring 16

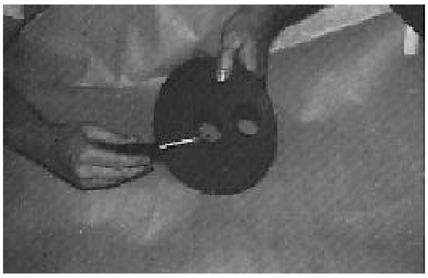
Picture 6: Tapping Securing Ring 11 into Position



Picture 7: Removing Port Nut 7 (left-hand threaded)

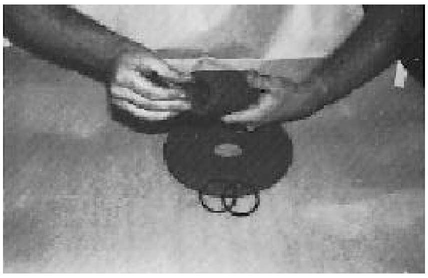
Picture 8: Pressing out Permeate Port 6

Picture 9: Removing Port Retainer Set 5



Picture 10: Removing Port Seals 9

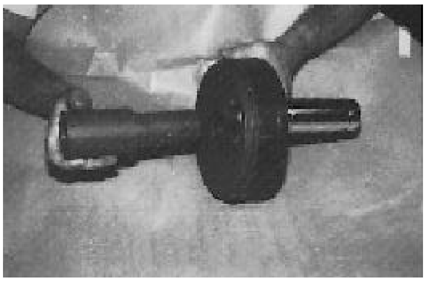
Picture 11: End Plug Disassembled



Picture 12: Installing Seals

Picture 13: Installing Feed/Concentrate Port 4

Picture 14: Installing Port Retainer Set 5



Picture 15: Installing Permeate Port 6

Assembly Instructions

Installing the Vessel

Mount pressure vessel with drain holes down on horizontal members. Support vessels using saddles **13** and strap assembly **14** at distance **S,** recommended central span for two-point support. Tighten hold-down straps until snug. Provide overpressure protection for vessel set at not more than 105 % of design pressure.

Opening the Vessel

Read Precautions.

Relieve pressure from vessel. Disconnect vessel ports from piping manifolds (Picture 1).

A. Use an Allen wrench to remove securing screws **12** from securing ring **11** (Picture 2). As each screw is removed, thread it into the adjacent hole until it contacts bearing plate **2.**

B. After transferring securing screws **12,** tap face of bearing plate **2** with a cushioned mallet or hammer and wood block to free locking ring set **10.**
CAUTION: Do not strike ports **4, 6;** this could cause severe damage.

C. To remove securing ring **11,** alternately turn securing screws **12** clockwise one and one-half to two turns. Do not cock securing ring; this could cause screws to jack securing ring off bearing plate **2.**

D. Remove key segment (long segment with two bevelled ends) first to free two other mirror-image segments. Rotate each of these segments to top of end plug; they will drop from groove (Picture 3).

E. Before removing end plug, clean pressure tube entrance and apply a thin coat of glycerine to segmented ring groove area. Grasp feed/ concentrate port **4** and, if attached, fitting connected to permeate **6.** Pull end plug straight out (Picture 4). It may be necessary to rock end plug slightly or give it a forceful tug to remove it.

F. Inspect pressure vessel inside diameter for dirt and foreign objects and clean as required.

Loading the Elements

A. Follow instructions for closing vessel in the following section. First end assembled will be opposite feed end. Thrust ring **16** will be in place.

B. Lubricate U-cup seal lightly with glycerine. Install U-cup seal with open end of U-cup facing feed end of vessel onto RO element. See illustration, U-cup Seal Detail.

C. Lubricate two o-rings **18** lightly with glycerine and install onto adaptor **15.** Install seal end of the adaptor into element opposite the feed end.

D. With vessel in a horizontal position, slide element in, keeping open side of U-cup seal facing feed end of vessel. Adaptor **15** will seat into permeate port **6** (first element only).

E. Lubricate four o-rings **20** lightly with glycerine and place in appropriate grooves on coupler **19.**

F. With a slight twisting motion, gently insert one end of coupler **19** into product water (center) tube of element. Element will accept approximately one-half of coupler.

G. Repeat steps B and D for next element.

H. Insert exposed portion of coupler **19,** also with a slight twisting motion, into product water tube on end opposite feed end of second element. Elements will touch each other. Maintain element alignment carefully during assembly process. Do not allow element weight to be supported by coupler. Misalignment can result in damage to permeate tubes.

I. Repeat steps F, G and H until all elements have been coupled and inserted. Final element will not have the coupler inserted in feed end of product water tube.

J. Lubricate with glycerine two remaining o-rings **18** and install on adaptor into element product water tube on feed end.

K. Remaining is feed end of vessel. Thrust ring is not required on this end. Follow instructions for installing End Plug and Interlock.

Parts Description
A.S.I. PVE-8 Pressure Vessel

Item	Quantity Required	Description	P/N 400 PSI	P/N 600 PSI	P/N 1,000 PSI
1	1	Shell	not sold separately		
2	2	Bearing Plate	81114	81162	81161
3	2	Sealing Plate	81115	81115	81115
4	2	Feed/Concentrate Port	81116	81116	81152
5	2	Port Retainer Set	81117	81117	81117
6	2	Permeate Port	81118	81118	81153
7	2	Port Nut	81119	81119	81119
8	2	End Plug Seal	81120	81120	81120
9	4	Port Seal (2-225)	80476	80476	80476
10	2	Locking Ring Set	81121	81121	81154
11	2	Securing Ring	81122	81122	81122
12	6	Securing Screw	81123	81123	81123
13	2	Saddle	81124	81155	81074
14	2	Strap Assembly	81125	81125	81125
15	2	Adaptor	81126	81126	81156
16	1	Thrust Ring	81127	81127	81127
17	2	Adaptor O-Ring (2-221)	80477	80477	80477
18	4	PWT O-Ring (2-119)	80478	80478	80478
19	One less than number of Elements	Coupler	81283	81283	81282
20	4 per Coupler	Coupler O-Rings (2-119)	80478	80478	80478

Pressure Vessel Complete is avaliable in sizes to house on to seven FILMTEC® elements.

Closing the Vessel

Installing the End Plug.

A. Apply glycerine to shell chamfer and walls about ½ inch from chamfer. Wear protective gloves or finger cots to prevent cuts or penetration by glass fiber particles.

B. Install thrust ring **16** at down-stream end of vessel (Picture 5).

C. Place adaptor o-ring **17** in groove on the permeate port **6.** Lubricate lightly with glycerine.

D. Apply glycerine to 8" diameter quad ring **8** and install onto end plug assembly.

E. Slide factory-assembled end plug into the shell. It should be square to shell wall. End plug design ensures permeate port **6** will mate with adaptor **15.**

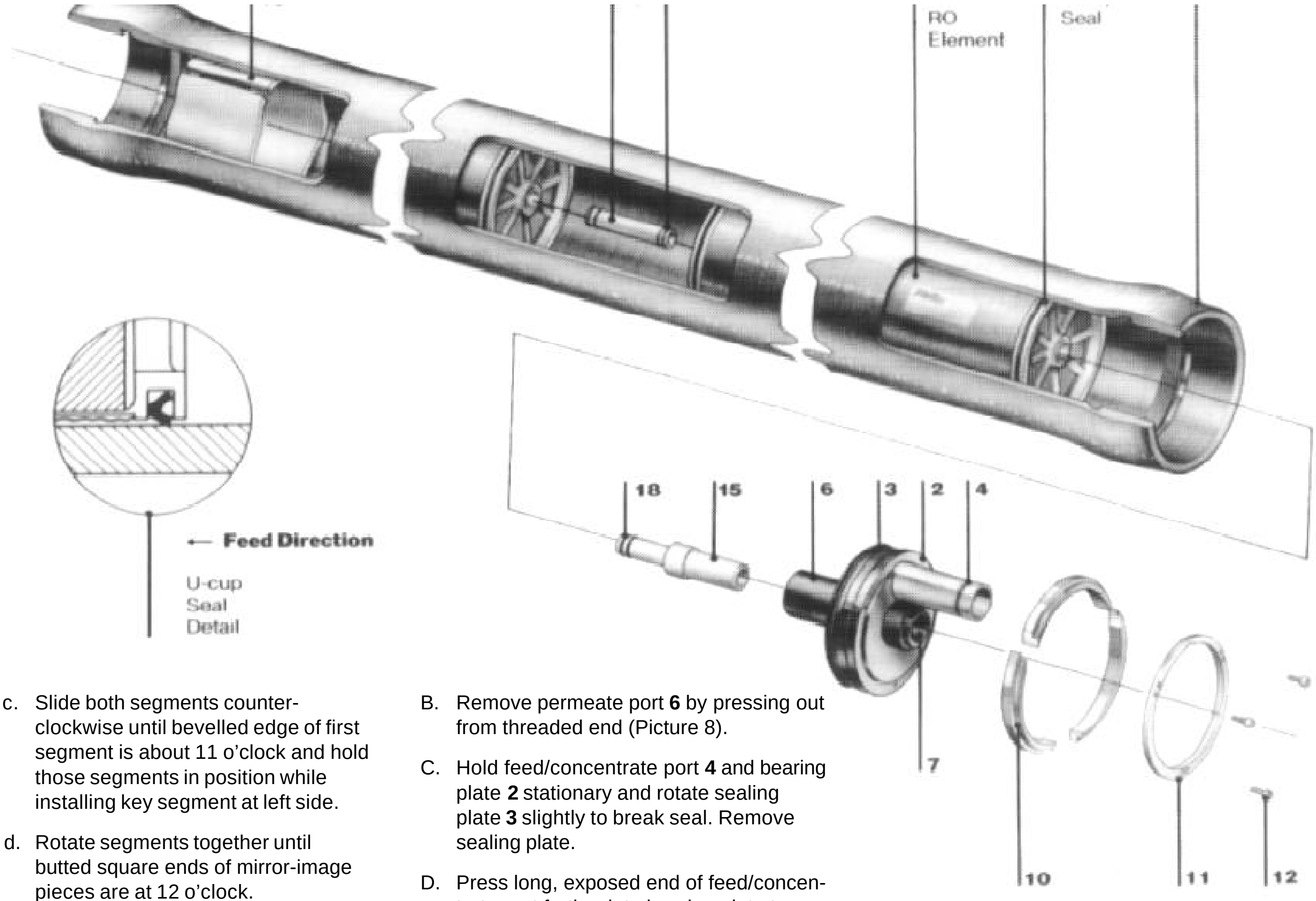
F. Push end plug with both hands until it will go no further.

Installing the Interlock.

A. Install locking ring set **10** with stepped edge facing out, as follows:

   a. Install one of mirror-image segments at bottom of shell in groove between shell reinforcing ring and end plug to square end of segment facing right.

   b. Slide first segment counter-clockwise, making room to install second mirror-image segment at bottom until its square end butts up against square end of first segment.



c. Slide both segments counter-clockwise until bevelled edge of first segment is about 11 o’clock and hold those segments in position while installing key segment at left side.

d. Rotate segments together until butted square ends of mirror-image pieces are at 12 o’clock.

B. Orient securing ring **11** with its feed/concentrate port **4** cutout at 12 o’clock. Hang ring on port and slide it in until securing screws **12** can be threaded into bearing plate **2.** Do not push securing ring into seated position against bearing plate until securing screws are started or cross-threading will result.
CAUTION: Do not use securing screws **12** to draw securing ring **11** into place; this may break screws. If holes in securing ring do not align precisely with tapped holes in bearing plate 2, reversing securing ring should improve alignment.

C. Thread securing screws **12** into bearing plate **2** one to one-half turns.

D. Once all three screws are started, use a screw driver to tap all the way around on securing ring 11 until it is fully seated on bearing plate **2** (Picture 6).

E. Tighten securing screws **12** until snug. Do not overtighten; screws may break.

F. Visually inspect locking ring set **10** to verify it is fully seated. Also verify securing ring **11** is fully seated and held in place by securing screws **12.**
CAUTION: Integrity, reliability and safe operation of vessel depend on correct installation of interlock components.

➧ End Plug Rebuilding

To control the end plug for corrosion, it must be disassembled:

A. Remove permeate port nut **7** by unscrewing left-hand thread (Picture 7).

B. Remove permeate port **6** by pressing out from threaded end (Picture 8).

C. Hold feed/concentrate port **4** and bearing plate **2** stationary and rotate sealing plate **3** slightly to break seal. Remove sealing plate.

D. Press long, exposed end of feed/concentrate port further into bearing plate to free the port retainer set **5.**

E. First remove port retainer set (2 pieces), then feed/concentrate port from the bearing plate (Picture 9).

F. Carefully remove two port seals **9** (Picture 10) and one end plug seal **8** from the sealing plate and one adaptor O-ring **17** from the permeate port.

Clean and examine all components (Picture 11). Replace damaged parts. Replacement of all seals is recommended. The end plug must then be carefully reassembled:

A. Slightly lubricate each seal with glycerine. Install port seals **9** in sealing plate **3** and adaptor O-ring **17** in permeate port **6** (Picture 12).

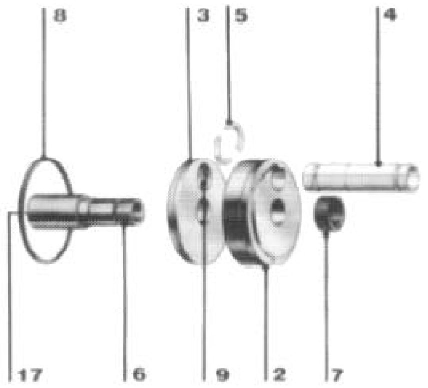
B. Hold the bearing plate **2** so that the stepped surface is facing toward you. From this side, insert the smaller, machined end of the feed/concentrate port **4** through the off-center hole (Picture 13).

C. Install the port retainer set **5** into the groove in the machined end of the feed/concentrate port (Picture 14). Pull port back until retaining ring set bottoms in bearing plate recess.

D. Hold these components together so that the retaining ring set remains firmly seated. With its larger diameter facing the bearing plate, press the sealing plate onto the machined end of the feed/concentrate port.

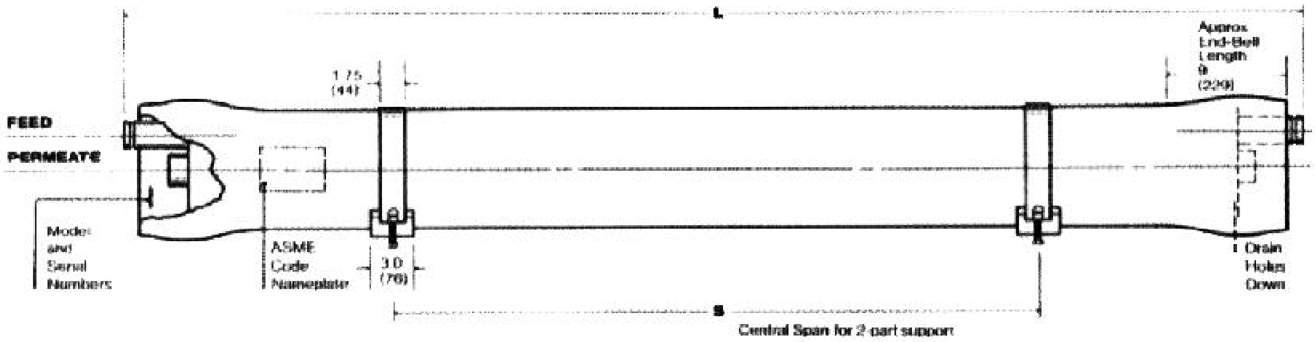
E. Rotate sealing plate until the two center holes are aligned.

Factory Assembled End Plug
Exploded View



F. From sealing plate side, insert threaded end of permeate port through bearing/sealing plate combination (Picture 15).

G. Thread port nut **7** (left-hand thread) onto permeate port. Tighten until snug.
CAUTION: With the port nut tightened the sealing plate must sit flush against the bearing plate. If any gap is evident, the components have not been correctly assembled. Incorrect assembly can result in catastrophic failure!



Precautions

Read and follow instructions. Failure to take every precaution will void warranty and may result in vessel failure. The A.S.I. PVE-8 pressure vessel must be installed and maintained in accordance with the precautions listed and good industrial practice to assure safe operation over a long service life. The high performance FRP shell must be allowed to expand under pressure; undue restraint at support points or piping connections can cause leaks to develop in the shell. The end closure, incorporating close-fitting, interlocking metal components, must be kept dry and free of corrosion; deterioration can lead to catastrophic mechanical failure of the end plug.

Do not make rigid piping connections to ports or clamp vessel to restrict expansion of shell under pressure. At design pressure, expansion will be 0.5 mm (0.02 in) in diameter and 13 mm (0.5 in) in length for a six-element vessel.

Do not hang piping manifolds from ports or use vessel to support other components. Branch connection piping may be supported between the header and port. Maximum weight of branch piping: feed/concentrate – 7 kg (16 lbs); permeate – 4 kg (8 lbs).

Do not operate vessel at pressures and temperatures in excess of its rating.

Provide overpressure protection for vessel, set at not more than 105 % of design pressure.

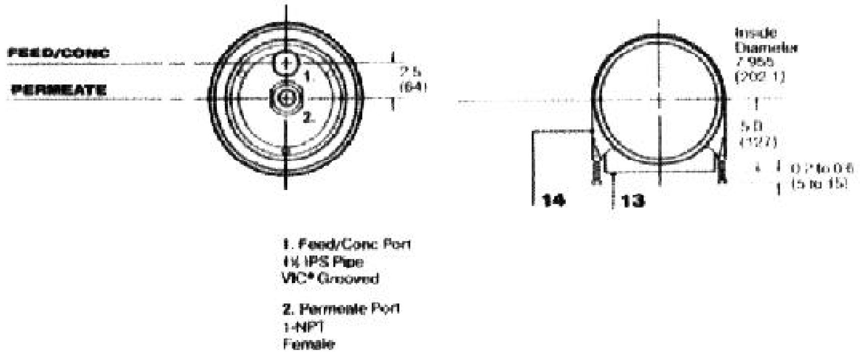
Do not operate vessel with permeate port pressure in excess of 9 bar (125 PSI) at 49°C.

Do not tighten permeate port connection more than one turn past hand tight.

Do not tolerate leaks or allow end closures to be routinely wetted in any way.

Do not pressurize vessel until verifying the locking ring set is in place and the securing ring is fully seated and secured by securing screws.

Do not work on any component before verifying pressure is relieved from the vessel.



Dimensions expressed as
inch (millimeter)

Length and Assembly Weight

PVE-8 pressure vessels are available in 3 pressure ratings: 28 bar (400 PSI), 41 bar (600 PSI) and 69 bar (1,000 PSI), and in sizes to house one to seven FILMTEC® elements. The length L, the central span S for 2-part support and the empty weight of all 8-inch vessels is given in the following tables:

Table

No. of Elements	L		S		Empty Wt	
	mm	(In)	mm	(In)	kg	(Lb)
PVE-8-400						
1	1,600	(63.0)	864	(34)	27	(60)
2	2,616	(103.0)	1,422	(56)	36	(80)
3	3,632	(143.0)	2,032	(80)	45	(100)
4	4,648	(183.0)	2,642	(104)	54	(120)
5	5,664	(223.0)	3,251	(128)	63	(140)
6	6,680	(263.0)	3,810	(150)	73	(160)
7	7,696	(303.0)	(3 Pts.)		82	(180)
PVE-8-600						
1	1,600	(63.0)	864	(34)	36	(80)
2	2,616	(103.0)	1,422	(56)	48	(105)
3	3,632	(143.0)	2,032	(80)	61	(135)
4	4,648	(183.0)	2,642	(104)	73	(160)
5	5,664	(223.0)	3,251	(128)	86	(190)
6	6,680	(263.0)	3,810	(150)	98	(215)
7	7,696	(303.0)	(3 Pts.)		111	(245)
PVE-8-1000						
1	1,651	(65.0)	864	(34)	52	(115)
2	2,667	(105.0)	1,422	(56)	70	(155)
3	3,683	(145.0)	2,032	(80)	91	(200)
4	4,699	(185.0)	2,642	(104)	109	(240)
5	5,715	(225.0)	3,251	(128)	129	(285)
6	6,731	(265.0)	3,810	(150)	147	(325)
7	7,747	(305.0)	(3 Pts.)		166	(365)

6. System Operation

6.1 Introduction

Successful long-term performance of the RO system depends on proper operation and maintenance of the system. This includes the initial plant start-up and operational start-ups and shut-downs. Preventing fouling or scaling of the membranes is not only a matter of system design, but also a matter of proper operation. Record keeping and data normalization is required in order to know the actual plant performance and to enable corrective measures when necessary. Complete and accurate records are also required in case of a system performance warranty claim.

6.2 Initial Start-Up

6.2.1 Equipment

The initial system start-up is typically performed just after the element loading. The material needed for element loading is listed in Section 5.1. For start-up, the following is also recommended:

- Safety glasses when working with chemicals
- Thermometer
- pH meter
- Conductivity meter (range: from permeate to brine conductivity)
- 3 or 4 clean 1 l plastic bottles (with plugs) for each pressure vessel for samples
- Analysis equipment for
  - Total hardness
  - Calcium
  - Alkalinity
  - Chloride
  - Sulfate
  - Iron
  - Silica
  - Free chlorine
  - Redox potential

6.2.2 Pre-Start-Up Check

After having loaded the elements into the pressure vessels and before starting up the RO unit, make sure that the whole pretreatment section is working in accordance with the specifications. If the pretreatment involved changing of the chemical characteristics of the raw water, then a full analysis of the water entering the RO unit must be made. Furthermore, absence of chlorine, turbidity and SDI must be determined.

The raw water intake must be stable with respect to:

- Flow
- SDI
- Turbidity
- Temperature
- pH
- Conductivity
- Bacteria (standard plate count)

The following checks of the pretreatment system and the RO unit are recommended for the initial start-up (results to be included in the start-up report):

Pre-Start-Up Checklist

❐ Corrosion resistant materials of construction are used for all equipment including piping and wetted parts of pumps

❐ All piping and equipment is compatible with designed pressure

❐ All piping and equipment is compatible with designed pH range (cleaning)

❐ All piping and equipment is protected against galvanic corrosion

❐ Media filters are backwashed and rinsed

❐ New/clean cartridge filter is installed directly upstream of the high pressure pump

❐ Feed line, including RO feed manifold, is purged and flushed, before pressure vessels are connected

❐ Chemical addition points are properly located

❐ Check valves are properly installed in chemical addition lines

❐ Provisions exist for proper mixing of chemicals in the feed stream

❐ Provisions exist for preventing the RO system from operating when the dosage pumps are shut down

❐ Provisions exist for preventing the dosage pumps from operating when the RO system is shut down

❐ If chlorine is used, provisions exist to ensure complete chlorine removal prior to the membranes

❐ Planned instrumentation allows proper operation and monitoring of the pretreatment and RO system (see Section 4.12.5)

❐ Planned instrumentation is installed

❐ Instrumentation is calibrated

❐ Pressure relief protection is installed and correctly set

❐ Provisions exist for preventing the product pressure from exceeding the feed/brine pressure more than 0.3 bar (5 PSI) at any time

❐ Interlocks, time delay relays and alarms are properly set

❐ Provisions exist for sampling permeate from individual modules

❐ Provisions exist for sampling feed, permeate and reject streams from each array and the total plant permeate stream

❐ Pressure vessels are properly piped both for operation and cleaning mode

❐ Pressure vessels are secured to the rack or frame

❐ Precautions as given in Section 5, Assembly and Loading of Pressure Vessels, are taken

❐ Membranes are protected from temperature extremes (freezing, direct sunlight, heater exhaust, etc.)

❐ Pumps are ready for operation (lubricated, proper rotation)

❐ Fittings are tight

❐ Permeate line is open

❐ Permeate flow is directed to drain

❐ Reject flow control valve is in open position

❐ Feed flow valve is throttled and/or pump bypass valve is partly open to limit feed flow to less than 50 % of operating feed flow

6.2.3
Start-Up Sequence

Proper start-up of reverse osmosis (RO) water treatment systems is essential to prepare the membranes for operating service and to prevent membrane damage due to overfeeding or hydraulic shock. Following the proper start-up sequence also helps ensure that system operating parameters conform to design specifications so that system water quality and productivity goals can be achieved. Measurement of initial system performance is an important part of the start-up process. Documented results of this evaluation serve as benchmarks against which ongoing system operating performance can be measured.

Before initiating system start up procedures, membrane pretreatment, loading of the membrane elements, instrument calibration, and other system checks should be completed. Following is the recommended RO system start up sequence:

Typical Start-Up Sequence

a. Before initiating the start-up sequence, thoroughly rinse the pretreatment section to flush out debris and other contaminants without letting the feed enter the elements. Follow the Pre-Start-up check described in Section 6.2.2.

b. Check all valves to ensure that settings are correct. The feed pressure control and concentrate control valves should be fully open.

c. Use low pressure water at a low flow rate to flush the air out of the elements and pressure vessels. Flush at a gauge pressure of 0.2 - 0.4 MPa (30 to 60 psi). All permeate and concentrate flows should be directed to an approved waste collection drain during flushing.

d. During the flushing operation, check all pipe connections and valves for leaks. Tighten connections where necessary.

e. After the system has been flushed for a minimum of 30 minutes, close the feed pressure control valve.

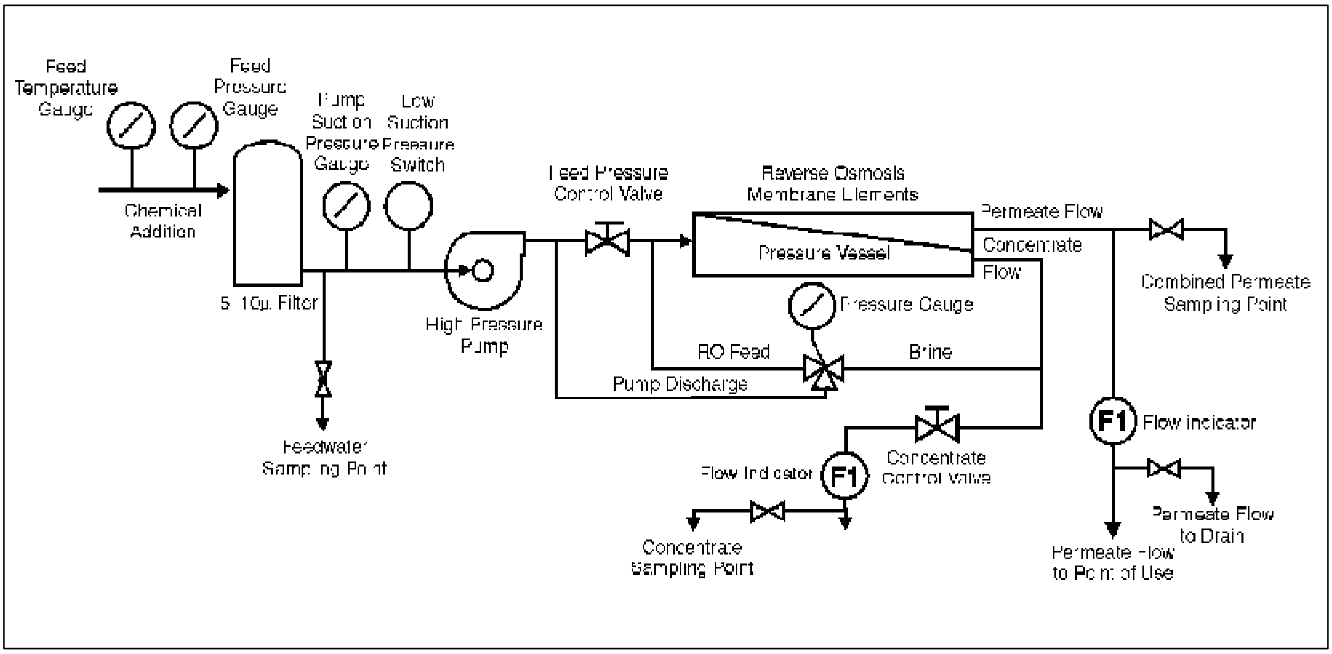
f. Ensure that the concentrate control valve is open.

g. Slowly crack open the feed pressure control valve (feed pressure should be less than 0.4 MPa/60 psi).

h. Start the high pressure pump.

i. Slowly open the feed pressure control valve, increasing the feed pressure and feed flow rate to the membrane elements until the design concentrate flow is reached. The feed pressure increase to the elements should be less than 0.07 MPa (10 psi) per second. Continue to send all permeate and concentrate flows to an approved waste collection drain.

Typical RO System



j. Slowly close the concentrate control valve until the ratio of permeate flow to concentrate flow approaches, but does not exceed, the design ratio (recovery). Continue to check the system pressure to ensure that it does not exceed the upper design limit.

k. Repeat steps "i" and "j" until the design permeate and concentrate flows are obtained.

l. Calculate the system recovery and compare it to the system's design value.

m. Check chemical additions of acid, scale inhibitor, and sodium metabisulfite (if used). Measure feedwater pH.

n. Check the Langelier Saturation Index (LSI) or the Stiff & Davis Stability Index (S & DSI) of the concentrate by measuring pH, conductivity, calcium hardness, and alkalinity levels and then making the necessary calculations.

o. Allow the system to run for one hour.

p. Take the first reading of all operating parameters.

q. Read the permeate conductivity from each pressure vessel and identify any vessels that do not conform to performance expectations (e.g., vessels with leaking O-rings or other evidence of malfunction).

r. After 24 to 48 hours of operation, read all plant performance data such as feed pressure, differential pressure, temperature flows, recovery and conductivity readings (please refer to Section 6.4, Record Keeping). At the same time draw samples of feedwater, concentrate, and combined system permeate and analyze sample constituents.

s. Compare system performance to design values.

t. Confirm proper operation of mechanical and instrumental safety devices.

u. Switch the permeate flow from drain to the normal operating position.

v. Lock the system into automatic operation.

w. Use the initial system performance information obtained in steps "p" through "r" as a reference for evaluating future system performance. Measure system performance regularly during the first week of operation to ensure proper performance during this critical initial stage.

6.3 Operation Start-Up

Once an RO membrane system has been started up, ideally it should be kept running at constant conditions. In reality, RO plants have to be shut down and restarted more or less frequently. Each start/stop cycle means pressure and flow changes, thus mechanical stress to the membrane elements. Therefore, the start/stop frequency should be minimized, and the regular operation start-up sequence should be as smooth as possible. In principle, the same sequence is recommended as for the initial start-up. Most important is a slow feed pressure increase, especially for sea water plants.

The checks before and during start-up can be performed as a routine and partly be automated. The valves can be operated by programmable motors. The calibration of instruments, the function of alarms and of safety devices, corrosion prevention and leak-free operation have to be checked on a regular basis.

6.4 Shutdown

When the RO membrane system is shut down, the feed pressure control valve is slowly closed, and the concentrate control valve is slowly opened, before the high pressure pump is switched off. Then the system must be flushed with either permeate water or high quality feed water, to remove the high salt concentration from the modules until concentrate conductivity matches feed water conductivity. Flushing is done at low pressure (about 3 bar/ 40 PSI). A high feed flow is beneficial for a cleaning effect; however a pressure drop of 1.4 bar (20 PSI) per element or 4.1 bar (60 PSI) per multi-element vessel must not be exceeded.

The water used for flushing shall contain no chemicals used for the pretreatment. Especially the scale inhibitors must be absent. Therefore the antiscalant dosing is stopped before flushing and also sulfuric acid dosing.

After flushing the system, the feed valve(s) is (are) closed completely. If the concentrate line ends into a drain below the level of the pressure vessels, then an air break has to be employed in the concentrate line at a position higher than the highest pressure vessel. Otherwise the vessels might be emptied by a syphoning effect.

When the system has to be shut down for extended periods of time longer than 48 hours, take care that:

- The elements do not dry out. Dry elements will irreversibly lose flux.
- The system is adequately protected against microbiological growth, or regular flushing is carried out every 24 hours.
- When applicable, the system is protected against temperature extremes.

The RO train can be stopped for 24 hours without preservation and precautions for microbiological fouling.

If feedwater for flushing every 24 hours is not available, preservation with chemicals is necessary for longer stops than 48 hours. Please refer to Section 8.3 for details.

6.5 Adjustment of Operation Parameters

6.5.1 Introduction

An RO membrane system is designed on the basis of a defined set of data such as the permeate flow, feedwater composition and temperature. In reality, the plant operation has to be flexible to respond to changing needs or changing conditions.

6.5.2 Brackish Water

The normal way of operating brackish water RO plants is to keep the flows and thus the recovery constant at the design values. Any change in the membrane flux, e.g. by temperature or fouling, are compensated by adjusting the feed pressure. However, the maximum specified feed pressure must not be exceeded, nor should too much fouling be tolerated (for cleaning, please refer to Section 7).

If the feedwater analysis changes such that the scaling potential increases, the system recovery has to be decreased, or other measures have to be taken to cope with the new situation. Please refer to Section 3, Water Chemistry and Pretreatment.

The most common situation is that the permeate capacity of the plant has to be adjusted to the needs. Normally, the capacity is designed to meet the peak needs. Operating with overcapacity is generally not recommended. Thus, adjustment means lowering the design permeate output. The easiest way is to shut the plant down when no permeate is needed. A high start/ stop frequency, however, can lower the performance and the lifetime of the membranes. A permeate buffer tank may be used to allow a more constant operation.

Reducing the feed pressure is another way to reduce the permeate flow. Preferably, this is done by using a speed controlled pump in order to save energy. Normally, the system recovery is kept constant when the permeate flow is reduced. It has to be ensured by a system analysis using the computer program, that single element recoveries do not exceed their limits (see Section 4, System Design). During low flow operation, the system salt rejection is lower than during design flow operation. Also, you must be certain that minimum concentrate flows are maintained during low flow operation.

The net permeate flow can also be reduced by recycling the excess permeate back to the feedwater. This allows to keep the hydraulic and pressure conditions for the membranes about constant. The permeate quality is improved during this operation, and the recycled permeate has a cleaning effect on the membranes.

6.5.3 Sea Water

In principle, the operation parameters of sea water plants are adjusted the same way as in brackish water applications. However, the maximum allowed feed pressure of 6.9 MPa (1000 PSI) and the permeate TDS are often the limiting factors.

Decreasing feedwater temperature can be compensated by increasing the feed pressure up to the maximum. Once the maximum pressure is reached, a further decreasing temperature causes the permeate flow to decrease. Increasing temperature is compensated by lowering the feed pressure. This is only possible, however, as far as the tolerated permeate TDS is not exceeded. Alternatively, increasing temperature can be compensated by taking a number of pressure vessels out of service. By reducing the active membrane area, the feed pressure and the permeate TDS are kept about constant. A system analysis has to be run to make sure that maximum element permeate flows are not exceeded. When some vessels are taken out of service, they have to be properly isolated and preserved.

An increase in the feedwater salinity can be compensated by increasing the feed pressure up to the maximum. If further pressure increase is not possible, than a lowered permeate flow and system recovery has to be accepted. A lower feedwater salinity allows to decrease the feed pressure and/or to increase the system recovery and/or to increase the permeate flow.

The adjustment of the permeate capacity to reduced needs is normally accomplished by sufficiently dimensional permeate tanks.

Big plants are split up into a number of identical trains. Then the number of trains in service can be adjusted to the needs.

6.6 Record Keeping

6.6.1
Introduction

In order to be able to follow the performance of the RO unit, it is necessary that all relevant data are collected, recorded and kept on file. Apart from keeping track of the performance, the logsheets are also valuable tools for troubleshooting, and are needed in the cases of warranty claims.

This chapter is for general guidance only and must not be used in place of the operating manual for a particular plant. Site-dependent factors prevent specific recommendations for all record keeping. Thus, only the more general record keeping is covered here.

6.6.2
Start-Up Report

- Provide a complete description of the RO plant. This can be done using a flow diagram and equipment, instrumentation, and material list to show water source, pretreatment system, RO configuration and posttreatment system.
- Give results of checking according to check list (Section 6.2.2).
- Provide calibration curves of all gauges and meters based on manufacturers' recommendations.
- Record initial performance of RO and pretreatment system as provided below.

6.6.3
RO Operating Data

The following data must be recorded and logged into an appropriate logsheet at least once per shift, unless otherwise stated (see Table 2 for an example).

- Date, time and hours of operation.
- Pressure drop per cartridge and per array.
- Feed, permeate and concentrate pressure of each array.
- Permeate and concentrate flows of each array.
- Conductivity of the feed, permeate and concentrate streams for each array. Permeate conductivity of each pressure vessel weekly.
- TDS of feed, permeate and concentrate streams for each array. The TDS is calculated from the water analysis. It can also be calculated from the conductivity (at 25°C) EC_{25} and an appropriate K factor:

  $$TDS = K\ EC_{25}$$

  The K factor has to be determined for each specific stream. Typical K factors are shown in Table 2 5).
- pH of the feed, permeate and concentrate streams.
- Silt Density Index (SDI) or turbidity of the RO feed stream, or both.
- Water temperature of the feed stream.
- Langelier Saturation Index (LSI) of the concentrate stream from the last array (for concentrate streams < 10,000 mg/l TDS).
- Stiff and Davis Stability Index (S&DSI) of the concentrate stream from the last array (for concentrate streams >10,000 mg/l).
- Calibration of all gauges and meters based on manufacturer's recommendations as to method and frequency but no less frequent than once every three months.
- Any unusual incidents, for example, upsets in SDI, pH and pressure and shutdowns.
- Complete water analysis of the feed, permeate and concentrate streams and the raw water at start-up and every week thereafter.

  The water analysis shall include:

  - Calcium
  - Magnesium
  - Sodium
  - Potassium
  - Strontium
  - Barium
  - Iron (total, dissolved and ferrous)
  - Aluminium (total and dis solved)
  - Bicarbonate
  - Sulfate
  - Chloride
  - Nitrate
  - Fluoride
  - Phosphate (total)
  - Silica (dissolved)
  - Total dissolved solids
  - Conductivity
  - pH
  - TOC

Table 1: Factors for Estimating TDS from Conductivity

Water	EC_{25}[1] (mS/m)	K
Permeate	0.1-1	0.50
	30-80	0.55
Sea water	4,500-6,000	0.70
Concentrate	6,500-8,500	0.75

[1] EC_{25} does not include the conductivity caused by dissolved CO_2 (see 10.4 page3)

Table 2: Reverse Osmosis Operating Log (Example)

Per Shift

Train #

		Design							
	Date								
	Time								
	Operating hours								
Pressure (psig)	Feed Array 1								
	Feed Array 2								
	Permeate								
	Concentrate								
Δ p (psid)	Cartridge								
	Array 1								
	Array 2								
Flow (gpm)	Feed								
	Permeate								
	Concentrate								
	Recovery (%)								
Conductivity (mS/m)	Feed								
	Permeate								
	Concentrate								
TDS (mg/l)	Feed								
	Permeate								
	Concentrate								
	Salt Passage (%)								
pH	Raw Water								
	Feed								
	Concentrate								
	Permeate								
Feed	Cl_2 (mg/l)								
	SDI								
	Turbidity (NTU)								
	Temperature (°C)								
Acid	Level								
	Refill (l)								
	Consumption (g/m^3)								
Inhibitor	Level								
	Refill (l)								
	Consumption (g/m^3)								
Nomalised	Permeate flow (gpm)								
	Salt Passage (%)								
	Remarks								

6.6.4
Pretreatment Operating Data

Since the RO system performance depends largely on the proper operation of the pretreatment, the operating characteristics of the pretreatment equipment should be recorded. Specific recommendations for all record keeping cannot be given, because pretreatment is site dependent. Typically, the following items must be recorded:

- Total residual chlorine concentration in the RO feed (daily - unless known to be completely absent).
- Discharge pressure of any well or booster pumps (twice a day).
- Pressure drop of all filters (twice a day).
- Consumption of acid and any other chemicals (daily - if used).
- Calibration of all gauges and meters based on manufacturers' recommendations as to method and frequency but no less frequent than once every 3 months.
- Any unusual incidents, for example, upsets and shutdowns as they occur.

6.6.5
Maintenance Log

- Record routine maintenance.
- Record mechanical failures and replacements.
- Record any change of membrane element locations with element serial numbers.
- Record replacements or additions of RO devices.
- Record calibration of all gauges and meters.
- Record replacement or additions of pretreatment equipment, for example cartridge filters and include date, brand name and nominal rating.
- Record all cleanings of RO membranes. Include date, duration of cleaning, cleaning agent(s) and concentration, solution pH, temperature during cleaning, flow rate and pressure (for cleaning procedures see Section 7).

6.7 Plant Performance Normalization

The performance of an RO system is influenced by the feed water composition, feed pressure, temperature and recovery. For example, a feed temperature drop of 4°C will cause a permeate flow decrease of about 10 %. This, however, is a normal phenomenon.

In order to distinguish between such normal phenomena and real performance changes, the measured permeate flow and salt passage have to be normalized, that means compared to a given reference performance while the influences of operating parameters are taken into account. The reference performance may be the designed performance or the measured initial performance.

Normalization with reference to the designed (or warranted) system performance is useful to verify that the plant gives the specified (or warranted) performance.

Normalization with reference to the initial system performance is useful to show up any performance changes between day one and the actual date.

This procedure is strongly recommended, because it allows an early identification of potential problems (e.g. scaling or fouling) when the normalized data are recorded daily. Corrective measures are much more promising when taken early.

A computer program called FTNORM is available for normalizing operating data and graphing Reg parameters including normalized permeate flow and salt passage as well as pressure drop. This program is available from Dow field sellers as Form No. 60900163 and requires Excel® software. Alternatively, the measured plant performance at operating conditions can be transferred to standard (reference) conditions by the following calculations:

A. Normalized Permeate Flow

$$Q_s = \frac{P_{f_s} - \frac{\Delta P_s}{2} - P_{p_s} - \pi_{fc_s}}{P_{f_o} - \frac{\Delta P_o}{2} - P_{p_o} - \pi_{fc_o}} \times \frac{TCF_s}{TCF_o} \times Q_o \qquad (1)$$

with P_f = feed pressure

$\frac{\Delta P}{2}$ = one half device pressure drop

P_p = product pressure

π_{fc} = osmotic pressure of the feed-concentrate mixture

TCF = temperature correction factor

Q = product flow

subscript s = standard condition

subscript o = operating condition

The temperature correction factor follows the formula:

$$TCF = EXP\ [2640 \times \{1 / 298 - 1 / (273 + T)\}];\ T \geq 25°C$$

$$= EXP\ [3480 \times \{1 / 298 - 1 / (273 + T)\}];\ T \leq 25°C$$

where T = temperature as °C.

As standard conditions, we take either the design values or the conditions at initial performance as given in the start-up report, so that a fixed reference point is available.

For the osmotic pressure, different formulas are available in the literature. A valid and practical short approximation is:

$$\pi_{fc} = \frac{C_{fc} \times (T + 320)}{491000} \text{ bar} \qquad \text{for } C_{fc} < 20000 \text{ mg/l}$$

and

$$\pi_{fc} = \frac{(0.0117 \times C_{fc}) - 34}{14.23} \times \frac{T + 320}{345} \text{ bar} \qquad \text{for } C_{fc} > 20000 \text{ mg/l}$$

with C_{fc} = concentration of the feed-concentrate

C_{fc} can be calculated from following approximation:

$$C_{fc} = C_f \times \frac{\ln \frac{1}{(1-Y)}}{Y}$$

where Y = recovery ratio = $\frac{\text{product flow}}{\text{feed flow}}$

C_f = TDS feed mg/l

B. The Normalized Permeate TDS is calculated from

$$C_{p_s} = C_{p_o} \frac{P_{f_o} - \frac{\Delta P_o}{2} - P_{p_o} - \pi_{fc_o} + \pi_{p_o}}{P_{f_s} - \frac{\Delta P_s}{2} - P_{p_s} - \pi_{fc_s} + \pi_{p_s}} \times \frac{C_{fc_s}}{C_{fc_o}} \qquad (2)$$

Terms not yet defined under A are:

C_p = product concentration as ion in mg/l

π_p = osmotic pressure of the permeate in bar

Example

- Values of Start-Up:

Feed water analysis in mg/l

Ca:	200	HCO_3:	152
Mg:	61	SO_4:	552
Na:	388	Cl:	633

Temp.:	15	°C (59 °F)				
Pressure:	363	bar	Pressure drop:	3	bar (43.5 psi)
Flow:	150	m^3/h (660 gpm)	Permeate pressure:	1	bar (14.5 psi)
Recovery:	75	%	Permeate TDS:	83	mg/l

- Values after 3 months:

Feed water analysis in mg/l:

Ca:	200	HCO_3^-:	152
Mg:	80	$SO_4^=$:	530
Na:	480	Cl:	850

Temp.:	10	°C (50 °F)		
Pressure:	28	bar (406 psi)	Pressure drop:	4 bar (58 psi)
Flow:	127	m^3/h (600 gpm)	Permeate pressure:	2 bar (29 psi)
Recovery:	72	%	Permeate TDS:	80 mg/l

For the standard conditions we have

P_{f_s} = 25 bar (363 psi)

$\frac{\Delta P_s}{2}$ = 1.5 bar (181.5 psi)

C_{f_s} = 1986 mg/l

$$C_{fc_s} = 1986 \times \frac{\ln \frac{1}{1 - 0.75}}{0.75} = 3671 \text{ mg/l}$$

π_{fc_s} = 2.5 bar (36.3 psi)

TCF_s = EXP [3480 x {1 / 298 – 1 / (273 + 15)}] = 0.67

For the operating conditions we have

P_{f_o} = 28 bar (406 psi)

$\frac{\Delta P_o}{2}$ = 2 bar (29 psi)

C_{f_o} = 2292 mg/l

$$C_{fc_o} = 2292 \times \frac{\ln \frac{1}{1 - 0.72}}{0.72} = 4052 \text{ mg/l}$$

π_{fc_o} = 2.72 bar (39.4 psi)

TCF_o = EXP [3480 x {1 / 298 – 1 / (273 + 10)}] = 0.54

Substituting these values in equations (1) gives:

$$Q_s = \frac{25 - 1.5 - 1 - 2.5}{28 - 2 - 2 - 2.7} \times \frac{0.67}{0.54} \times 127$$

$= 148\ m^3/h$ normalized flow (652 gpm)

Compared to the start-up conditions, the plant has lost 1.6 % capacity. This is very good for a period of 3 months. Cleaning is not yet necessary.

The normalized permeate TDS is given by

$$C_{p_s} = \frac{28 - 2 - 2 - 2.72 + 0.06}{25 - 1.5 - 1 - 2.5 - 0.05} \times \frac{3670}{4052} \times 80$$

$= 77$ mg/l

Compared to the initial 83 mg/l, the salt rejection has slightly improved. Such behavior is typical for the initial phase.

6.8 Control of Microbiological Activity

Biofouling is one of the most common and most severe problems in the operation of RO systems. Especially for plants using surface water or bacteriologically contaminated water as feed source, it is of paramount importance to control the microbiological activity. A properly designed and operated pretreatment is a prerequisite (see Section 3.6: Biological Fouling Prevention).

A complete procedure for sampling and analysis should be part of the operating discipline, so that any increase of the microbiological activity can be responded to at an early stage. The methods to assess the biological fouling potential are described in Section 3.6.2.

The sampling of microbiological activity can be done using pre-sterilized sampling containers, or coupons, such as Millipore or Robbin biofilm samplers or other dynamic simulations of microbiological activity and its distribution in the real system.

If the lab equipment needed for analysis of the microbiological samples is not available at the RO-plant site, an adequate lab should be found to perform the needed analysis.

If the analysis cannot be done at the site, the samples should be put in the refrigerator and the analysis performed within 8 hours of sampling.

Sampling Points
Adequate sampling points should be provided to make a microbiological balance and control in the plant possible. The minimum number of sampling points required are listed below:

1. Intake (surface) or well, before chlorination if any.
2. After a clarifier, settling pond, sludge contact unit or similar sedimentation process.
3. After filtration units (sand, multimedia, activated carbon or other).
4. After dechlorination (normally after cartridge filtration).
5. Concentrate stream.
6. Permeate stream.

The frequency of sampling and analysis depends on the risk of biofouling. For surface water plants, a daily check of the feed water (point 4) and a weekly check of all points is recommended.

System Checking
Before start-up and whenever problems related to microbiological activity are suspected, the following checks should be carried out:

- In case intermediate open basins or tanks are used, provisions should be made to ensure proper disinfection at that open source and the part of the system downstream from it.
- If intermediate sealed tanks are used, their air breathing or ventilation systems should be equipped with bacteria retaining devices (e.g. HEMA filters).
- Blind long pieces of piping should be avoided by design, and when unavoidable, should be periodically disinfected.
- Stand-by devices with large surfaces, like sand or cartridge filters should be avoided. If they are not avoidable, drains should be installed to discharge the disinfection chemicals after the devices have been disinfected, and before connecting them to the active system.

  The periodic disinfection of the pretreatment system should be done according to the biological loading of the raw water, the efficiency of the continuous breakpoint chlorination, and the specific characteristics of each individual plant design.

  In this sense, it is also recommended that the backwash of the media filters be done with sufficiently chlorinated water.

  In general terms, the water used for disinfection, flushing and to prepare cleaning solutions should be of good quality and free of biological life.
- The components of the pretreatment system such as pipes, manifolds, filters and retention tanks should be opaque to sunlight to avoid enhancing the biological growth.
- All piping, tanks, manifolds as well as the retention tanks, filters etc.; i.e. the whole pretreatment system shall be disinfected previous to each start-up, following shutdown times as well as periodically when the RO plant is being operated continuously. A good way to do it is by dynamic breakpoint chlorination of the system with the exception of the RO section. In this case RO section and in particular the FT30 membranes shall be protected from chlorine. The best way to protect them, is to physically isolate the RO section from the rest by using a flange. For these cases, a drain should be installed at a low point close to the flange.
- Adequate chemicals for storage, cleaning and disinfection should always be available at the RO plant site.

6.9 References

1) Youngberg, D.A.: Start-up of an RO/DI Pure Water System. Ultrapure Water, March/April 1986, 46-50.

2) ASTM D4472-89: Standard Guide for Record Keeping for Reverse Osmosis Systems.

3) ASTM D4516-85 (Reapproved 1989): Standard Practice for Standardizing Reverse Osmosis Performance Data.

4) ASTM D4195-88: Standard Guide for Water Analysis for Reverse Osmosis Application.

5) Walton, V.R.G.: Electrical Conductivity and Total Dissolved Solids – What is Their Precise Relationship? Desalination, 72 (1989) 275-292.

7. Cleaning and Disinfection

7.1 Introduction

The surface of RO membrane is subject to fouling by foreign materials which may be present in the feed water such as hydrates of metal oxides, calcium precipitates, organics and biological matter. (The term “fouling” here includes the build-up of all kinds of layers on the membrane surface, including scaling).

The pretreatment of the feedwater prior to the RO process is basically designed to reduce contamination of the membrane surfaces as much as possible. This is accomplished by installing an adequate pretreatment system and selecting optimum operating conditions such as permeate flow rate, pressure and permeate water recovery ratio.

Occasionally, fouling of the membrane surfaces is caused by

- inadequate pretreatment system
- pretreatment upset conditions
- improper materials selection (pumps, piping, etc.)
- failure of chemical dosing systems
- inadequate flushing following shutdown
- improper operation control
- slow build-up of precipitates over extended periods (barium, silica)
- change in feed water composition
- biological contamination of feed water

The fouling of membrane surfaces manifests itself in a performance decline, lower permeate flow rate and/or higher solute passage. Increased pressure drop between the feed and concentrate side can be a side effect of fouling.

Cleaning can be accomplished very effectively because of the FT30 membrane’s combination of pH stability and temperature resistance.

If the time of cleaning is delayed too long however, it is difficult to remove the foulants completely from the membrane surface. The cleaning will be more effective the better it is tailored to the specific fouling problem. Sometimes, a wrong choice of cleaning chemicals can even worsen the situation. Therefore, the type of foulants on the membrane surface should be determined prior to cleaning. There are different possibilities:

- Analyze the plant performance data. Details are given in Section 10: “Troubleshooting”.
- Analyze the feed water. A potential fouling problem may already be visible there.
- Check the results of previous cleanings.
- Analyze the foulants collected with a membrane filter used for SDI value determination.
- Analyze the deposits on the cartridge filter.
- Inspect the inner surface of the feed line tubing and the feed end scroll of the FILMTEC® element. If it is reddish-brown, fouling by iron materials may be considered. Biological fouling or organic material is often slimy or gelatinous.

7.2 Cleaning Requirements

Elements should be cleaned whenever:

- the normalized permeate flow drops by 10 percent,
- the normalized salt content of the product water increases by 10%,
- the differential pressure (feed pressure - concentrate pressure) ∆P increases by 15% from the reference conditions (initial performance established during the first 24 to 48 hours of operation).

It should be noted that it is important to normalize flow and salt content of the permeate according to the normalization procedure described in Section 6.7.

7.3 Safety Precautions

In using any chemicals mentioned in this section, follow accepted safety practices. Always wear eye protection as a minimum. In the case of handling corrosive chemicals (e.g. sulfuric acid) wear full face cover and protective clothing. Consult the relevant Material Safety Data Sheets as supplied by the manufacturer of the chemicals.

Check the materials of construction used in the cleaning system is adequate and compatible with the cleaning chemicals to be used. Never use aluminium as material in contact with the cleaning solution.

7.4 Cleaning Equipment

The equipment for cleaning is shown in the cleaning system flow diagram (Figure 1). The pH of cleaning solutions used with FILMTEC® elements can be in the range of 1 to 12, and therefore non-corrosive materials should be used in the cleaning system.

The mixing tank should be constructed of polypropylene or fiberglass reinforced plastic (FRP). The tank should be provided with a removable cover and a temperature gauge.

The cleaning procedure is more effective when performed at an elevated temperature. It is not recommended to use a cleaning temperature below 15°C (59°F) because of the very slow cleaning rate at low temperatures. In addition, chemicals such as sodium lauryl sulfate might precipitate at low temperatures. Cooling may also be required to avoid overheating, so heating/cooling requirements must be considered during the design.

A rough rule of thumb in sizing a cleaning tank is to use approximately the empty pressure vessel volume and then add the volume of the feed and return hoses or pipes.

For example, to clean eight 8-inch diameter pressure vessels with six elements per vessel, the following calculations would apply (for conversion of U.S. units into metric units see Section 10.7).

A. Volume in Vessels

$$V_1 = \pi r^2 \times L$$
$$= 3.14\,(4\text{ in})^2 \times (6 \times 40\text{ in})$$

$$V_1 = 200\text{ l/vessel}$$

$$V_8 = 200 \times 8 = 1600\text{ l}$$

B. Volume in Pipes, Assume 50 ft Length Total, SCH 80 Pipe

$$V_p = \pi r^2 \times L$$
$$3.14\,(50\text{ mm})^2 \times (30\text{ m})$$
$$= 236\text{ l}$$

$$V_{ct} = V_8 + V_p = 1600\text{ l} + 236\text{ l}$$
$$= 1836\text{ l}$$

Therefore, the cleaning tank should be about 450 gal.
The cleaning pump should be sized for the flows and pressures given in Table 1, making allowances for pressure drops in the piping and across the cartridge filter. The pump should be constructed of 316 SS or non-metallic composite polyesters.

Appropriate valves, flow meters, and pressure gauge should be installed to adequately control the flow. Service lines may be either hard piped or portable hoses. In either case, the flow rate should be less than 10 ft/sec.

permeate flow
Aldus Freehand 4.0
8/16/95 3:38 PM

TANK	Chemical Mixing Tank. polypropylene or FRP
IH	Immersion Heater (may be replaced by cooling coil for some site locations
TI	Temperature Indicator
TC	Temperature Control
LLS	Lower Level Switch to shut off pump
SS	Security Screen – 100 mesh
PUMP	Low Pressure Pump, 316 SS or non-metallic composite
CF	Cartridge Filter, 5–10 micron polypropylene with PVC, FRP or SS housing.
DP	Differential Pressure Gauge
FI	Flow Indicator
FT	Flow Transmitter (optional)
PI	Pressure Indicator
V1	Pump Recirculation Valve, CPVC
V2	Flow Control Valve. CPVC
V3	Concentrate Valve, CPVC 3 way valve
V4	Permeate Velve, CPVC 3 way valve
V5	Permeate Inlet Valve, CPVC
V6	Tank Drain Valve, PVC or CPVC
V7	Purge Valve, SS, PVC or CPVC

Figure 1: Cleaning System Flow Diagram

7.5 Cleaning Procedure

There are eight steps in the cleaning of reverse osmosis modules:

1. **Prepare and mix** the appropriate cleaning solution, and check pH of the solution. Ensure that all chemicals are dissolved and well-mixed before circulating the solution to the elements. Any cleaning solution must be clear.
2. **Low flow pumping.** Pump mixed, preheated cleaning solution to the vessel at conditions of low flow rate (about half of that shown in Table 1) and low pressure to displace the process water. Adjust flow rate and pressure by valves V1 and V2. Use only enough pressure to compensate for the pressure drop from feed to concentrate. The pressure should be low enough that essentially no permeate is produced. A low pressure minimizes redeposition of dirt on the membrane. Dump the concentrate, as necessary to prevent dilution of the cleaning solution.
3. **Recycle.** After the process water is displaced, cleaning solution will be present in the concentrate stream. Then recycle the concentrate to the cleaning solution tank and allow the temperature to stabilize. Observe the turbidity of alkaline or detergent solutions to judge efficiency. If the cleaning solution colors or becomes turbid, restart with a freshly prepared cleaning solution. Check the pH during acid cleaning. The acid is consumed when it dissolves inorganic precipitates. So if the pH increases more than 0.5 pH units, add more acid.
4. **Soak.** Turn the pump off and allow the elements to soak. Sometimes a soak period of about 1 hour is sufficient. For difficult fouling an extended soak period is beneficial; soak the elements overnight for 10-15 hours. To maintain a high temperature during an extended soak period, use a slow recirculation rate (about 10% of that shown in Table 1).
5. **High flow pumping.** Feed the cleaning solution at the rates shown in Table 1 for 30-60 minutes. The high flow rate flushes out the foulants removed from the membrane surface by the cleaning. If the elements are heavily fouled, which should never happen, a flow rate which is 50% higher than shown in Table 1 may aid cleaning. At higher flow rates excessive pressure drop may be a problem. The maximum recommended drops are 1.4 bar (20 PSI) per element or 4.1 bar (60 PSI) per multi-element vessel, whichever value is more limiting. For 8" elements, the direction of flow during cleaning must be the same as during normal operation to avoid telescoping of the elements.

Table 1: Recommended Feed Flow Rate per Pressure Vessel during High Flow Rate Recirculation

Element Diameter (in)	Feed Flow Rate per PV (GPM)	Feed Flow Rate per PV (m^3/h)
2.5	3 - 5	0.7 - 1.1
4	8 - 10	1.8 - 2.3
8	30 - 40	7 - 9

6. **Drain** the spent cleaning solution out of the system. Recommendation: Take a sample of the spent and of the fresh cleaning solution. From the results of a chemical analysis, you can determine the amount of substances removed from the membrane elements.
7. **Flush out.** RO permeate or good quality water (filtered, SDI < 3, free of bacteria and chlorine, conductivity < 10,000 µS/cm) is used for flushing out the residual cleaning solution. To prevent precipitation, the minimum flush out temperature is 20°C. Before starting up the plant with normal operating pressures and flows, the bulk of the cleaning solution must be flushed from the elements.
8. **Rinse out.** The RO plant is started up again resuming normal operating conditions. As cleaning chemicals will be present on the permeate side after cleaning, the permeate must be discharged to drain for at least 10 minutes (or until the required permeate quality is obtained) when starting up after cleaning. When another cleaning cycle with another cleaning chemical is to follow, make sure that the permeate side of the module is rinsed out as well. Otherwise a chemical reaction with the following cleaning chemical may happen.

During the rinse out step, the operating parameters should be noted to judge the cleaning efficiency and to decide if another cleaning is required.

If the system has to be shut down after cleaning for longer than 24 hours, the elements should be stored in a preservation solution (see Section 8: Handling and Preservation).

For multi-array (tapered) systems, cleaning should be carried out separately for each array (except rinse out), so the flow rate is not too low in the first array or too high in the last. Also, any deposits removed from the first array will not be carried all the way through the following arrays where they might clog the feed channels.

This can be accomplished either by using one cleaning pump and operating one array at a time, or using a separate cleaning pump for each array.

A multi-array system can also be cleaned successively in groups of about equal numbers of parallel vessels. For example, a 8:4 staged system can be cleaned in 3 groups each with 4 vessels in parallel. This allows an optimum selection of the cleaning pump.

7.6 Cleaning Chemicals

The FT30 membrane's chemical stability allows a wide range of cleaning chemicals to be used. However, there is no sharp borderline between cleaning chemicals not affecting the membrane performance, and cleaning chemicals affecting the membrane performance. The cleaning chemicals and cleaning conditions recommended here are such, that the specified element performance is not affected after three years of operation when the cleaning chemicals or cleaning conditions are applied for 2 hours once a week.

Harsh and frequent cleaning will shorten the membrane life (typically by increased salt passage), while mild and seldom cleaning will extend the membrane life (anticipated that no fouling occurs).

Table 2 lists suitable cleaning chemicals. Acid cleaners and alkaline cleaners are the standard cleaning chemicals. The acid cleaners are to remove inorganic precipitates including iron, while the alkaline cleaners are to remove organic fouling including biological matter. Sulfuric acid should not be used for cleaning because of the risk of calcium sulfate precipitation.

Preferably, reverse osmosis permeate should be used for the cleaning solutions but prefiltered raw water will also work in most cases. The raw water can be highly buffered, so more acid or hydroxide may be needed with raw water to reach the desired pH level, which is about 2 for acid cleaning and about 12 for alkaline cleaning.

During cleaning, the pH range and maximum temperatures as given in Table 3 must not be exceeded. **Brand name cleaning chemicals are** frequently used in the field rather than self-made formulations. Some cleaning chemicals, however, worsen the performance of the clean membrane, e.g. by fouling and subsequent flux loss. Before brand name cleaning chemicals are used, their compatibility with FILMTEC® FT30 elements has to be secured.The procedure for compatibility testing is a long-term cleaning test on a new FILMTEC element under the harshest recommended cleaning conditions. A soak test with FT30 membrane coupons can be used as a screening test. A chemical compatability testing procedure is described in section 10.11 of this manual.

The cleaning chemicals listed in Table 4 have shown FT30 compatibility in short-term tests (cleaning efficacy has not been tested!).They can be used, provided the membrane plant performance is carefully monitored to detect any long term effects at an early stage. When cleaning, follow the cleaning chemical manufacturer's instructions and observe the pH limits of the membrane (Table 3).

Table 2: Simple Cleaning Solutions for FT30 Membrane

Cleaner Foulant	0.1% (W) NaOh and pH 12,30°C max. or 1.0% (W) Na_4EDTA and pH12,30°C max	0.1% (W) NaOH and pH 12,30°C max. or 0.025%& Na-DDS and pH12,30°C max	0.1% STP and 1.0% Na_4EDTA or 0.1% TSP and 1.0% Na_4EDTA	0.2% (W) HCl	0.5% (W) H_2PO_4	2.0% (W) Citric Acid	0.2% (W) NH_2SO_3H	1.0% (W) $Na_2S_2O_4$
Inorganic Salts (for example, Cac3, CaS_4, $BaSO_4$)				best	OK	OK	OK	
Metal Oxides (for example iron)					good		OK	good
Inorganic Colloids (silt)		good						
Silica	OK							
Biofilms	best	good	good					
Organic OK	good	good						

1. (W) denotes weight percent of active ingredient.

2. Cleaning chemical symbols, in order used: NaOH is sodium hydroxide; Na-EDTA is the sodium salt of ethylene diamine tetraacetic acid; Na-DDS is sodium salt of dodecylsulfate; STP is sodium triphosphate ($Na_5P_3O_{10}$); TSP is trisodium phosphate ($Na_3PO_4 \times 12H_2O$); HCl is hydrochloric acid; H_3PO_4 is phosphoric acid; citric acid is $C_3H_4(OH)(CO_2H_3)$; NH_2SO_3H is sulfamic acid; $Na_2S_2O_4$ is sodium hydrosulfite.

Table 3: pH Range and Temperature Limits During Cleaning

	Max Temp 50°C pH Range	Max Temp 35°C pH Range	Max Temp 30°C pH Range	Continuous Operation
SW30, SW30 HR	3-10	2-11	2-12	2-11
BW30, TW30	2-10	1-11	1-12	2-11
NF45, SR90	3-10	2-11	1-11	3-9

Table 4: Short Term Compatible Brand Name Cleaning Chemicals

ARGO-Bioclean 511, Argo Scientific
ARGO-Bioclean 882, Argo Scientific
ARGO-IPA 403, Argo Scientific
ARGO-IPA 411, Argo Scientific
ARGO-AES 510, Argo Scientific
ARROW-TREAT 2100

ARROW-TREAT 2200
ARROW-TREAT 2300

Dia 707, Argo Scientific
Diamite-FT, King-Lee
Diamite-FT, Antimicrobial, King Lee
Divos 115, Diversey Wyandotte
Feedmate 151, Grace

Filtrapure, Acid
Filtrapure TF
Floclean 403, FMC
Floclean 411, FMC
Gambro WRO
Henkel P3-ultrasil 10 (1% soak test)
Henkel P3-ultrasil 70
Henkel P3-ultrasil 75 (1% soak test)
Jal/Nas 30 0.1% + 0.1NaOH
KL 2000, King-Lee
KL 3000, King-Lee
Klenzade KX-6713B
Mic Chem Cleaner (4% soak test)

Monarch 972-0-1 (5% soak test)
Monarch 972-0-2 (5% s.t.)
Monarch 972-0-3 (5% s.t.)
Monarch 2024-11-7 (0.5%)
Monarch Enzyme Cleaner 96

MT 1000 F, BF Goodrich
MT 2000 F, BF Goodrich
MT 2100, BF Goodrich
MT 3000 F, BF Goodrich
MT 4000, BF Goodrich

Scaleclean 87, Grace

Test concentration was double the recommended strength unless otherwise stated.

7.7 Disinfecting RO Systems

7.7.1
Introduction

If the plant has been infected by bacteria or mold, a disinfection must be carried out after the cleaning. The procedure is the same as for cleaning, except that the high flow pumping step can be skipped.

7.7.2
Formaldehyde

Formaldehyde can be used as a disinfectant with 0.5 to 3.0% concentrations. Care should be taken in handling this chemical and in flushing the system after use.

7.7.3
Hydrogen Peroxide and Peracetic Acid

Hydrogen peroxide or **hydrogen peroxide/peracetic acid** solutions can be used at concentrations up to 0.2%. The biocidal efficacy of peracetic acid is much higher than that of hydrogen peroxide, but as most peracetic acid solutions also contain hydrogen peroxide, care must be exercised not to exceed the 0.2% concentration as a sum of both compounds. Continuous exposure at this concentration may eventually damage the membrane. Instead, periodic use is recommended.

When hydrogen peroxide is applied, **the pH of the solution must be lower than 4.** A pH of 3 is recommended. This will ensure optimal biocidal results and longer membrane lifetime. If no acid is added to the hydrogen peroxide solution, the chemical attack on the membrane will be much faster. When a mixture with peracetic acid is used, pH adjustment is usually not required.

If an alkaline cleaning has preceded disinfection, the alkalinity has to be carefully rinsed out also from the permeate side (check pH!) before peroxide/peracetic acid is applied. Otherwise the membrane might become oxidized.

Two other factors greatly influence the rate of hydrogen peroxide attack on the membrane: temperature and iron.

The disinfecting solution must not exceed 25°C. FT30 membrane samples tested with 0.5% hydrogen peroxide at 34°C showed a very high salt passage after several hours. At 24°C however, membrane samples demonstrated compatibility with 0.5% hydrogen peroxide after 96 hours.

Iron or other transition metals must not be present, because they catalyze membrane degradation in the presence of hydrogen peroxide solutions. FT30 samples were tested using a 0.15% solution of hydrogen peroxide and tapwater containing iron. After 150 hours, the salt passage of the membrane began to increase dramatically.

For RO systems using the FT30 membrane, Dow recommends the following procedure for disinfection with hydrogen peroxide solutions:

1. Any type of deposit on the membrane or other parts of the system should be removed with an alkaline cleaner before disinfecting. Removal of these deposits, which harbor microorganisms, will maximize the degree of disinfection. After alkaline cleaning, flush the system with RO permeate.
2. Clean the RO system with acid, e.g. 0.1% by volume hydrochloric acid or 0.4% by volume phosphoric acid, to remove any iron from the membrane surface. Flush the unit with RO permeate.
3. Circulate a solution of 0.2% hydrogen peroxide (preferably containing peracetic acid) diluted with RO permeate and pH adjusted to 3-4 with HCl at a temperature below 25°C for 20 minutes.
4. Allow the elements to soak in the disinfecting solution for 2 hours.
5. Flush out the disinfecting solution. Rinse the system.

7.7.4.
Chlorinated Disinfectants

FILMTEC® FT30 membrane can withstand short-term exposure to free chlorine (hypochlorite); however, its resistance is limited. The membrane can be used successfully in installations where system upsets result in temporary exposure to free chlorine. Eventual degradation may occur after approximately 200-1,000 hours of exposure to one ppm concentrations of free chlorine. The rate of chlorine attack depends on various feedwater characteristics. Under alkaline pH conditions, chlorine attack is faster than at neutral or acidic pH. Chlorine attack is also faster at higher concentrations of heavy metals (e.g. iron), which catalyze membrane degradation. As in many cases there will be some iron fouling on the membrane, the intended use of chlorinated disinfectants should not be considered.

Disinfection with agents containing combined chlorine is generally not recommended. This includes such compounds as chloramine, chloramine-T, and N-chloroisocyanurate. FT30 is resistant to mild chlorinating agents such as these at low concentration (< 3 mg/l).

However, their effectiveness as disinfectants at low concentrations is limited. These compounds can also slowly damage the membrane, since they are in equilibrium with small amounts of free chlorine. When used, the pH must be <8.

7.7.5
Other Disinfectants

Iodine, quaternary germicides, and phenolic compounds cause flux losses and are not recommended for use as disinfectants.

70% ethanol can be used for disinfection. **Brand name biocides** have also been tested for effects on the membrane performance.[1] There are fully compatible and limited compatible biocides.

Those biocides which have limited compatibility can be in contact with the membrane for two hours a week for at least 3 years without any significant effect on the membrane performance. However, in continuous contact, a change in membrane performance might be detectable after a few weeks. The biocides with limited compatibility are listed in Table 1.
Biocides with full compatibility can be in contact with the membrane continuously for at least one year without significant loss of salt rejection and permeate flux (cleaning may be required, however, after long term disinfection). Those biocides can also be used for preservation (see also Section 8). Table 2 lists the fully compatible biocides:

Table 1: Brand Name Biocides with limited FT30 Compatiblity (for intermittent use)

Biocide	Max. Concentration (20-25°C)	Supplier
Rogun 881	200 ppm	Argo Scientific
Bactipal SN	1%, pH < 4	Seppic
Dow Antimicrobial 7287	200 ppm	Dow Chemical
Minncare	1%, pH < 4	Minntech
Renalin	1%, pH < 4	Minntech

Table 2: FT30 Compatible Brand Name Biocides

Biocide	Max. Concentration (20-25°C)	Supplier
Bioclean 882	0.2 %	Argo Scientific
C-68	0.09 %	Betz
Kathon GC/ICP	0.15 %	Rohm and Haas
Nalco 2593	0.15 %	Nalco
Monarch Soak 40	5 %	Monarch Chemical
Filtrapure Membrane Preservative	1 %	Monarch Chemical

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[1] For the biocidal efficacy, contact the supplier.

7.8 Cleaning and Disinfection Programs

Different degrees of cleaning processes can be applied to FT30 membrane depending on the foulants. These cleaning processes range from a simple flushing with prefiltered water up to a complicated cleaning program including different harsh cleaning chemicals and disinfectants. Cleaning processes may be ranked in the following order:

1. Forward flush with pretreated raw water (high feed flow, low feed pressure).
2. Cleaning with permeate.

3a. Cleaning with sodium hydrosulfite, acid or alkaline at pH well within the limits.

3b. Disinfection with formaldehyde or fully approved biocide.

4a. Cleaning with acid or alkaline at pH limits.

4b. Disinfection with hydrogen peroxide.

5. Cleaning with formulations containing EDTA.
6. Cleaning program with different cleaning chemicals and/or disinfectants. A cleaning/disinfection program may include soft or harsh chemicals.

When the optimum cleaning process is to be selected, the following has to be considered:

- Minimize impact on the environment by spent cleaning solutions (e.g. EDTA, biocides).
- Optimize foulants removing efficacy.
- Minimize impact on membranes (prefer mild chemicals).
- Minimize cleaning costs.

Examples of cleaning processes tailored to specific situations are given below. The list is not meant to be complete.

➧ A. Situation: Organic Fouling, no Biofouling
Cleaning: Soft Alkaline

a. Follow instructions in Section 7.3 and 7.4. Clean each array separately.
b. Flush with permeate or good quality water [1] for 5 minutes.
c. Prepare cleaning solution:

Na-EDTA	(0.2%)
NaOH	(< 0.1%, pH 11)
Na-Laurylsulfate	(0.1-0.2%) [2]

d. Circulate about 1 hour.
e. Soak 2-6 hours [3].
f. Drain the cleaning solution out of the system.
g. Flush with permeate or good quality water for 5 min.

Notes:
- Measure temperature and pH before and during each of the indicated steps.
- Limit temperature to 30°C (86°F).
- Prepare cleaning solution with permeate or good quality water [1].
- Restart the RO plant within 10 hours after finishing the cleaning, or, in cases of prolonged shutdown, preserve the membranes.

➧ B. Situation: Organic Fouling, Biofouling Expected
Cleaning: Soft Alkaline and Disinfection

a. Follow instructions in Section 7.3 and 7.4. Clean each array separately.
b. Flush with permeate or good quality water [1] for 5 minutes.
c. Prepare cleaning solution:

Na-EDTA	(0.2%)
NaOH	(< 0.1%, pH 11)
Na-Laurylsulfate	(0.1-0.2%) [2]

d. Circulate about 1 hour.
e. Soak 2-6 hours [3].
f. Drain the cleaning solution out of the system.
g. Flush with permeate or good quality water for 5 min.
h. Prepare a 0.5-1% formaldehyde [4] solution.
i. Circulate about 45-60 minutes.
j. Drain formaldehyde solution out of system.
k. Flush the plant with permeate or good quality water [1] for about 10 to 15 minutes.

Notes:
- Measure temperature and pH before and during each of the indicated steps.
- Limit temperature to 30°C (86°F).
- Prepare cleaning solution with permeate or good quality water [1].
- Restart the RO plant within 10 hours after finishing the cleaning, or, in cases of prolonged shutdown, preserve the membranes.

[1] Filtered water, SDI < 3, free of bacteria and chlorine, conductivity < 10,000 µs/cm.
[2] Na-Laurylsulfate improves cleaning, but it can be omitted in case it is not available.
[3] The soaking time can be reduced to about 2 hours if the cleaning solution is recirculated every 30 minutes for about 10-30 minutes.
[4] Refer to Section 7.7.2 for cautions when using formaldehyde with FT30 membrane.

➧ C. Situation: Carbonate Scaling, Metal Oxides, Hydrolyzed SHMP [=]
Cleaning:

a. Follow instructions in Section 7.3 and 7.4. Clean each array separately.
b. Flush with permeate or good quality water [1] for 5 minutes.
c. Prepare cleaning solution: 0.7% Henkel P3-ultrasil 70.
d. Circulate about 20 min at 30-35°C (86-95°F) or 30 min at 20-30°C (68-86°F).
e. Drain the cleaning solution out of the system.
f. Flush with permeate or good quality water [1] for 5 min.
g. Restart the RO plant, and after stabilization of the operation (about 1 hour after steady operation) measure operating parameters to control efficiency of the cleaning.

Notes:
- Measure and record temperature and pH before and during each of the indicated steps.
- Prepare cleaning solution with permeate or good quality water [1].
- In case the pH of the freshly prepared cleaning solution increases by more than 1 pH unit during recirculation (e.g. from pH 2.5 to pH 3.8 after 5 minutes recycle), please adjust the pH to the original one by carefully adding concentrated cleaning chemical.

[=] Sodium hexa meta phosphate can precipitate as calcium phosphate, when hydrolyzed.
[1] Filtered water, SDI < 3, free of bacteria, conductivity < 10,000 µS/cm.

➧ D. Situation: Type of Foulants not Known
Cleaning: Soft Alkaline / Disinfection / Acid

a. Follow instructions in Section 8.3 and 8.4. Clean each array separately.
b. Flush with permeate or good quality water [1] for 5 minutes.
c. Prepare cleaning solution:

c. Prepare cleaning solution:	Na-EDTA	(0.2%)
	NaOH	(< 0.1%, pH 11)
	Na-Laurylsulfate	(0.1-0.2%) [2]

d. Circulate about 1 hour.
e. Soak 2-6 hours [3].
f. Drain the cleaning solution out of the system.
g. Flush with permeate or good quality water [1] for 5 min.
h. Prepare a 0.5-1% formaldehyde [4] solution.
i. Circulate about 45-60 minutes.
j. Drain formaldehyde solution out of system.
k. Flush the plant with permeate or good quality water [1] for about 10 to 15 minutes.
l. Prepare a 0.1% HCl solution (pH » 2).
m. Circulate about 1 hour.
n. Flush the plant with permeate or good quality water [1] for about 10 to 15 minutes.

Notes:
- Measure temperature and pH before and during each of the indicated steps.
- Limit temperature to 30°C (86°F).
- Prepare cleaning solution with permeate or good quality water [1].
- Restart the RO plant within 10 hours after finishing the cleaning, or, in cases of prolonged shutdown, preserve the membranes.

[1] Filtered water, SDI < 3, free of bacteria and chlorine, conductivity < 10,000 µs/cm.
[2] Na-Laurylsulfate improves cleaning, but it can be omitted in case it is not available.
[3] The soaking time can be reduced to about 2 hours if the cleaning solution is recirculated every 30 minutes for about 10-30 minutes.
[4] Refer to Section 7.7.2 for cautions when using formaldehyde with FT30 membrane.

7.9 Emergency Cleaning

When cleaning has not been carried out in time, e.g. the differential pressure ΔP has already doubled, or the normalized product flow has dropped by 50%, the success of previously described cleaning processes may be limited. If those standard cleaning techniques fail to remove the foulants, more harsh cleaning methods can be tried.

Please contact your Dow representative for recommendations. It has to be stressed however, that no warranty can be given on the efficiency of any cleaning, nor on the membrane performance after such cleaning attempts.

8. Handling and Preservation

8.1 General

FILMTEC® membrane elements should be handled in such a way that biogrowth and change in membrane performance during long-term storage, shipping, or system shut-downs is prevented. The elements should preferably be stored and shipped outside the pressure vessels and loaded into the pressure vessels just prior to start-up.

In using biocide solutions as membrane preservations, follow accepted safety practices. Always wear eye protection. Consult the relevant Material Safety Data Sheets as supplied by the manufacturer of the chemicals.

8.2 FILMTEC Element

8.2.1
Preservation

New FILMTEC® elements are shipped in a standard preservation solution containing 1% sodium bisulfite and 20% propylene glycol. All these elements have been tested by quality control, soaked in the mentioned solution for one hour, drained, and bagged into a double plastic bag. The inner bag is made out of an oxygen barrier material.

Bisulfite provides protection from biological growth, propylene glycol provides protection from freeze damage and has additional preserving properties.

Some types of FILMTEC elements are also available as dry elements. Those elements have not been individually tested. They are bagged into a single plastic bag. They do not require any preservation solution, but they shoud be kept in their sealed bag until they are used.

Any FILMTEC element that has been used and removed from the pressure vessel for storage or shipping, must be preserved in a preservation solution. Use a mixture of 1% (by weight) of sodium bisulfite – food grade, not cobalt activated – and 20% (by weight) propylene glycol. Glycol can be omitted when freezing temperatures can be excluded. Soak the element for one hour in the solution, allow to drip out, and seal it into an oxygen barrier plastic bag. We recommend re-using the original bag or original spare bags available from Dow. 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. Identify the element and the preservation solution on the outside of the bag.

Instead of sodium bisulfite, formaldehyde can be used as preservation solution at 0.5 to 3.0% (by weight) concentration. 0.5% is sufficient when no biofilm is on the membrane. Formaldehyde is a more effective biocide than bisulfite and is not decomposed by oxygen. On the other hand, formaldehyde handling requires more precautions due to its suspected carcinogenicity. Please follow the relevant safety regulations. Refer to Section 7.7.2 when using formaldehyde.

Elements must be in use for at least six hours before formaldehyde is used as a biocide. If the elements are exposed to formaldehyde before being in use for this period of time, a loss in flux may result.

Aldehydes other than formaldehyde do not affect the membrane rejection, but the water permeability may be markedly decreased. Therefore, no other aldehydes are recommended as preservation solution components.

The fully approved biocides listed in Table 2 of chapter 7.7 can also be used as membrane preservatives. They do not affect the membrane performance, but their biocidal efficiency cannot be guaranteed.

Elements that have dried out after use may irreversibly lose water permeability. Re-wetting might be successful with one of the following methods:

- Soak in 50/50% ethanol/water or propanol/water for 15 min.
- Pressurize the element at 10 bar (150 PSI) and close the permeate port for 30 min. Take care that the permeate port is reopened before the feed pressure is released.
- Soak the element in 1% HCl or 4% HNO_3 for 1-100 hours.

8.2.2
Storage

Please follow these guidelines for storage of FILMTEC elements:

- Store cool inside a building or warehouse and not in direct sunlight.
- Temperature limits: -4°C to +45°C (22° to 113°F). New dry elements will not be affected by temperatures below -4°C (22°F).

  Elements stored in 1% sodium bisulfite/20% propylene glycol will freeze below -4°C, but as the ice crystals are soft, the membrane will not be damaged.
- Keep new elements in their original packaging.
- Storage time of dry elements is unlimited.
- Elements preserved in bisulfite/glycol should be visually inspected for biological growth every three months. When the preservation solution appears to be not clear, or after six months, the element should be removed from the bag, soaked in a fresh preservation solution and repacked.

  In case no equipment for re-preservation (fresh solution, clean environment, bag sealing device) is available, the elements can be left in their original packaging for up to 12 months. When the elements are then loaded into the pressure vessels, they should be cleaned with an alkaline cleaner before the plant is started up.
- The pH of the preservation solution must never drop below pH 3. A pH decrease can occur when bisulfite is oxidized to sulfuric

acid. This precaution is especially important for sea water membranes (SW30 and SW30HR), because the salt rejection of those membranes will be affected at low pH storage. Therefore, the pH of the bisulfite preservation solution should be spot checked at least every 3 months. Representation is mandatory when the pH is 3 or lower.

- Elements stored in formaldehyde do not need frequent observation. The preservation solution should be renewed after 12 months.

8.2.3
Shipping

When FILMTEC elements have to be shipped, they must be preserved with a preservation solution according to Section 8.2.1.

Make sure that:

- the plastic bag does not leak,
- the element is properly identified,
- the preservation solution is correctly labeled.

We recommend using the original packaging with the polystyrene foam cushions to protect the element from mechanical damage. The product tube ends of elements of size < 8" are especially endangered.

8.2.4
Disposal

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

- no preservation solution or other hazardous liquid is contained in the element,
- no depositions of hazardous substances are on the membranes (e.g. elements used in waste water treatment).

8.3 RO system

The procedure of shutting down an RO system has been described in Section 6.4. FILMTEC elements have to be preserved any time the plant is shut down for more than a maximum of 48 hours in order to prevent biological growth. Depending on the previous operational history of the plant, it will be necessary in almost all cases to perform a cleaning of the RO membranes prior to shutdown and preservation. This applies to cases when the membranes are known or assumed to have a certain fouling.

A typical sequence for the cleaning can be as follows:

Perform a soft alkaline cleaning at pH=11 for 2 hours, disinfect and perform a short acid cleaning. In case the plant has been operated with a feed free of scalants and metal hydroxides, the acid cleaning can be omitted. For more details, please refer to Section 7 (Cleaning and Disinfection).

After cleaning and disinfection, the preservation should follow within the next 10 hours as follows:

a. Preservation of the plant using “total immersion” of elements into a solution of 1 to 1.5% of sodium metabisulfite, 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. At the end of the pressure vessel’s filling, the SMBS solution shall be allowed to overflow through an opening located higher than the upper end of the highest pressure vessel being filled.

b. Separate the preservation solution from the air outside by closing all valves. Any contact with oxygen will oxidize the SMBS.

c. Check the pH once a week. When the pH becomes 3 or lower, change the preservation solution.

d. Change the preservation solution at least once a month.

During the shutdown period, the plant must be kept frost-free, and the temperature must not exceed 45°C (113°F). A low temperature is desireable.

9. Troubleshooting

9.1 Introduction

Loss of salt rejection and loss of permeate flow are the most common problems encountered in reverse osmosis. If the salt rejection and/or the permeate flow decreases slowly, this may indicate a normal fouling/ scaling which can be handled by proper and regular cleaning (see Section 7: Cleaning and Disinfection). A rather fast or an immediate performance decline indicates a defect or misoperation of the plant. In any case, it is essential that the proper corrective measure is taken as early as possible, because any delay decreases the chance of restoring the plant performance – apart from other problems that might be created by an excessively low permeate flow and/or too high permeate TDS.

A prerequisite for early detection of potential problems is proper record keeping (see Section 6.6) and plant performance normalization (see Section 6.7). This includes proper calibration of all instruments. Without accurate readings it might be too late before a problem can be detected and corrected.

Once a performance decline has been identified, the first step in solving the problem is to localize the problem and to identify the cause(s) of the problem. This can be done using the data of the record keeping logsheet or of some additional on-line measurements.

If these data are not sufficient to determine the cause(s) and to recommend corrective action, one or more membrane elements must be taken from the plant and analyzed. Element performance analysis includes nondestructive and destructive analysis.

The contents of this section have partly been adapted from a series of articles published in “Ultrapure Water” 1).

9.2 Localization of High Salt Passage

A loss in salt rejection may be uniform throughout the system or it could be limited to the front or to the tail end of the system. It could be a general plant failure or it could be limited to one or few individual vessels. Therefore, all individual vessel TDS values have to be checked. A well-designed system contains a sample port located in the permeate stream from each vessel. Care must be taken during sampling to avoid mixing of the permeate sample with permeate from other vessels. All permeate samples are then tested for their concentration of dissolved solids with a TDS meter.

The permeate samples of all pressure vessels in the same array should give readings in the same range. Notice that from one array to the next the average permeate TDS usually increases, because for example the second array is fed with the concentrate from the first array. To determine the salt passage of all modules from their permeate TDS, the TDS of the feed stream to each array must also be measured. The salt passage is the ratio of the permeate TDS to the feed TDS. Then the high salt passage of the system can be assigned to the first or the last array, or to individual vessels.

If one pressure vessel shows a significantly higher permeate TDS than the other vessels of the same array, then this vessel should be probed. Probing involves the insertion of a plastic tube (approx. 1/4" for 8" module) into the full length of the permeate tube (see Figure 1). This can be accomplished by removing the vessel's product manifolds or by removing the opposite end cap's product plug. When the product manifolds remain in place, it must be ensured that no permeate from other vessels can influence the probing.

While the RO system is operating at normal operating conditions, water is diverted from the permeate stream of the vessel in question. 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 with a hand-held meter and the data be recorded. This measurement should reflect the TDS of the permeate being produced by the FILMTEC® element at that position.

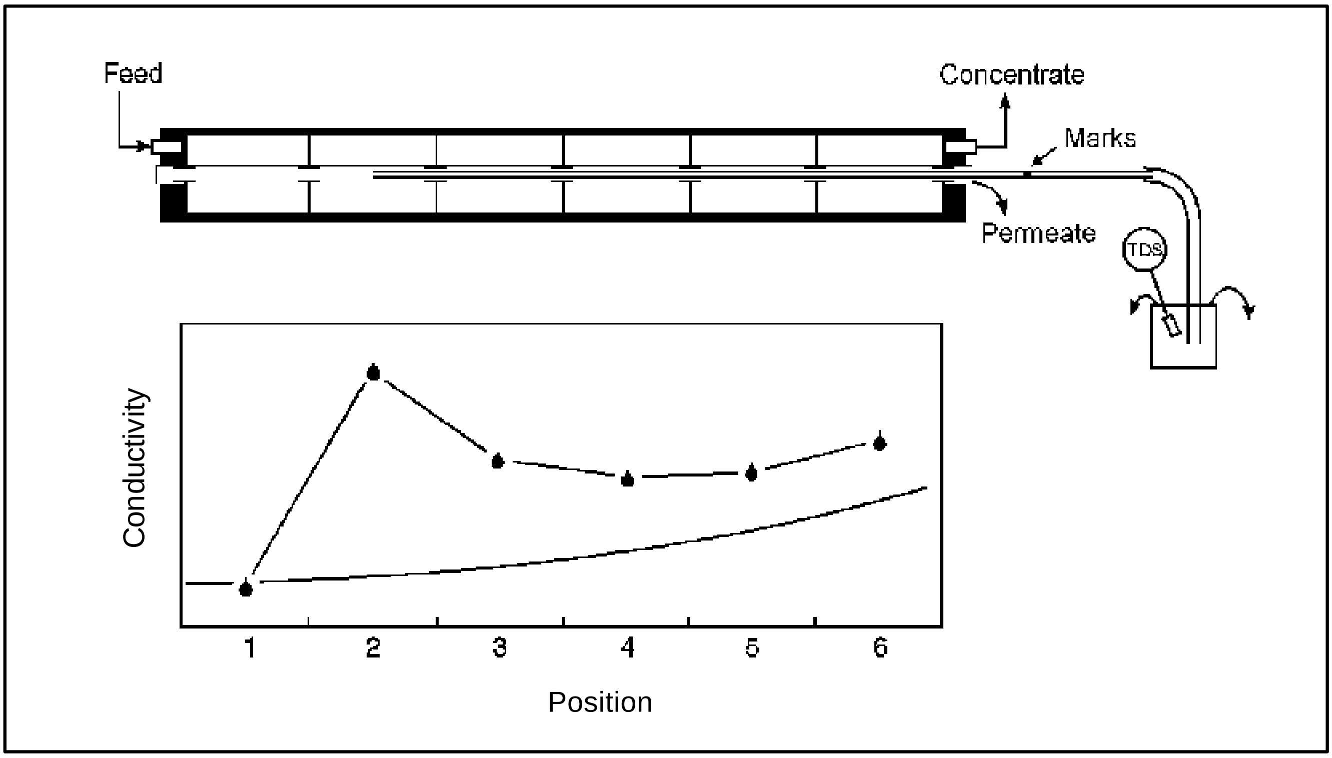


Figure 1: Conductivity Profile

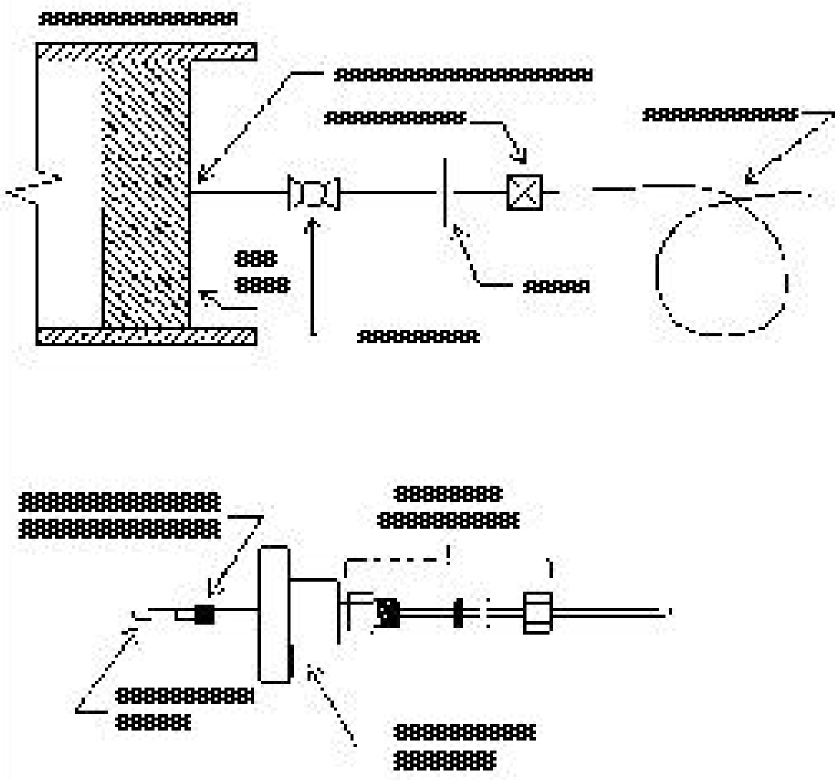
The tubing is then pulled out to the next element and another sample is taken. This sample represents a blend of the permeates of the first and of the second element. The tubing is then withdrawn in further increments to obtain a conductivity profile (see Figure 1). The sampling locations should be at the middle of the element and at the ends of the element (to check coupler/adaptor O-rings). The tube can be marked so that the desired sampling locations can easily be accessed.

The conductivity of a probe sample is the average of product water produced upstream. Better results in the sense of measuring the permeate TDS being actually produced at the location of sampling can be obtained when the permeate exits both ends of the vessel.

A normal conductivity profile shows a steady increase of the permeate produced at the feed side of the pressure vessel towards the concentrate end of the vessel. An unusually large deviation from this profile locates the source of the high salt passage problem. O-ring problems are generally indicated by a step change in the conductivity profile at coupler/adaptor locations, while a marked increase outside this region points to an element problem.

9.2.1
Product Tube Probing apparatus for spiral wound membrane elements

Multi-element pressure vessels can be permeate probed with the use of a $^1/_2$ inch ball valve connected to the opposite end of the pressure vessel from the product header piping. The ball valve is fitted with a $^1/_4$ inch plastic Parker tube fitting which has been modified by drilling the body to allow a $^1/_4$ inch nylon probe tubing to pass completely through the fitting. Use of the modified tube fitting eliminates water leakage at the point of entry (see Figure 2). In addition a short piece (2 inches) of very supple thin wall gum rubber tubing which fits snugly over the end of the nylon probe tubing and protrudes approximately $^1/_2$ inch will prevent hangups at the product tube adaptors and the product tube interconnectors.



* NOTE:
TUBE FITTING MODIFIED BY EXTENDING THE $^1/_4$ INCH BORE THROUGH THE BODY AND DISCARDING THE GRIPPER RING.

Figure 2: Permeate probing apparatus for spiral wound membrane

9.3 Element Analysis

9.3.1
Sample Selection

When the causes of a plant performance loss are not known, or when they have to be confirmed, one or more elements of the system have to be analyzed individually. The element(s) which should be analyzed are those with a step increase in the 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 fouling problems; typical tail-end problems are scaling problems. When the problem cannot be localized, an element from both ends of the system should be taken.

Sampling a second element from a neighbor position is advisable when cleaning tests are planned. Then one of the elements can be used to analyze the fouling layer and to perform lab scale cleaning tests, the results of which can then be applied to the other element.

9.3.2
Leak Test

A FILMTEC® element with a high salt passage should first be checked if leaks are present in which there is a direct communication between the feed/concentrate side and the permeate side. Leaks may occur through damage of the membrane surface itself by punctures or scratches or by glue-line failure. The following method may be used to detect leaks or to confirm the mechanical integrity of a FILMTEC element [2)].

This test, also called a vacuum test, is useful as a screening procedure and is not intended as a means of absolute verification of leaks. Only leaks which are significant enough to prevent the element from holding a vacuum are detected.

a. Drain the element.
b. Seal one end of the permeate tube with a suitable leak-tight cap (not necessary for TW30-1512, TW30-1812, and TW30-4611 elements). Connect the other end of the permeate tube to a vacuum gauge and a valved vacuum source.
c. Evacuate the element to 100 to 300 mbar absolute pressure. Close the isolation valve and observe the reading on the vacuum gauge. Note the rate at which the vacuum decays. A rapid decay (greater than 200 mbar per minute) will indicate the presence of a leak.
d. Slowly release the vacuum and allow the element to reach atmospheric pressure before disconnecting.

9.3.3
Standard Test

The standard element test is used to determine the desalinating ability and permeate flow rate of a FILMTEC element under FILMTEC Standard Test Conditions. The test results can then be compared with the specification of the element in question. The element performance is determined before and after any cleaning trial in order to assess the efficacy of the treatment.

The apparatus for the standard test consists of a feed holding tank equipped with a thermostated heat exchanger system to maintain the feed solution at 25±1°C, a booster pump, a high pressure pump, and a reverse osmosis device. A detailed description is given in ASTM D4194-89 [3)]. A sodium chloride solution is used as feed water. Permeate and concentrate are recycled back to the feed tank.

The NaCl concentration and the feed pressure are given in the Standard Test Conditions in the Technical Bulletin of the relevant FILMTEC element. The feed flow rate should be adjusted to obtain the element recovery as indicated in the mentioned Standard Test Conditions. The feed water pH should be adjusted to a pH of 8 by adding HCl or NaOH.

The following data are recorded one hour after start-up, and repeated 2 to 3 hours after start-up, and hourly thereafter until three successive permeate flow rates (corrected to 25°C) and salt passages agree within 5% (relative):

- Feed, concentrate, and permeate pressures
- Permeate and concentrate flows (use calibrated flow meters or a calibrated volume container and stopwatch)
- Permeate temperature
- Conductivity of feed, permeate and concentrate, or chloride content of the three streams.

The permeate flow rate should be corrected to 25°C using the formulas given in Section 6.7, Plant Performance Normalization. The salt rejection is calculated from the permeate conductivity K_p and the feed conductivity K_f:

$$\text{Rejection, \%} = \left(1 - \frac{K_p}{K_f}\right) \times 100$$

9.3.4
Cleaning Test

When the permeate flow rate of the tested element is too low compared with the specified value, a cleaning can be tried. Cleaning cannot be successful however, when the membrane itself is damaged, or when the membrane is heavily fouled/scaled (typically when the permeate flow is < 50% of specification).

Cleaning is carried out according to the cleaning procedure described in Section 7 (Cleaning and Disinfection).

When the cleaning test has proven effective, the treatment can be applied to the whole RO system.

9.3.5
Destructive Analysis

The ultimate method to determine the cause(s) of a performance loss is the destructive analysis (autopsy) of the FILMTEC® element. The Technical Service and Development Department of Dow must be involved if destructive analysis is required in warranty cases.

When the endcaps and the wrapping of the element have been removed, the membrane leave(s) can be unrolled. A visual inspection of the membrane surface and the glue lines can provide valuable information. A massive fouling layer, if present, can be sampled for chemical analysis.

Ashing of a membrane sample with known surface area and subsequent analysis of the residual oxides provides quantitative data of the composition of a fouling/scaling layer.

The morphology of deposits is determined with a stereo and standard light microscope or a scanning electron microscope (SEM).

A semi-quantitative analysis of the chemical elements contained in the membrane or its fouling/scaling layer is obtained from an X-ray analysis. This method can also furnish evidence of halogen damage to the membrane.

Oxidation damage can be made visible by cutting coupons out of the membrane leaves and operating them in a plate and frame test unit (Lab 20) with a methylene blue dye solution. The membranes treated in this manner show a more or less equally colored back side, while the back side of an undamaged membrane remains white.

9.4 Causes and Corrective Measures

9.4.1 High Salt Passage

9.4.1.1 High Permeate Flow

a. Membrane Oxidation
A high salt passage in combination with a higher than normal permeate flow is mostly due to oxidation damage. When free chlorine, bromine, ozone, or other oxidizing chemicals are present in the incoming water, the front end elements are typically more affected than the others. A neutral to alkaline pH favors the attack to the membrane.

Oxidation damage may also occur by disinfecting with oxidizing agents, when pH and temperature limits are not observed (see Section 7.7). In this case, a uniform damage is likely.

A FILMTEC® element with oxidation damaged membrane is still mechanically intact when tested with the vacuum test (see Section 9.3.2). The chemical membrane damage can be made visible by a dye test on the element or on membrane coupons (see Section 9.3.5). Autopsy of one element and analysis of the membrane can be used to confirm oxidation damage. No corrective action is possible. All damaged elements must be replaced.

b. Leak
Severe mechanical damage of the element or of the permeate tubing can allow feed or concentrate to penetrate into the permeate, especially when working at high pressures. The vacuum test will show a distinct positive response. Possible causes are discussed in the next section.

9.4.1.2 Normal Permeate Flow
High salt passage at normal permeate flow may have different causes.

a. Leaking O-Ring
Leaking O-rings can be detected by the probing technique (Section 9.2). Inspect O-rings of couplers, adaptors, and end plugs for correct installation and as-new condition. Replace old and damaged O-rings. O-rings may leak after exposure to certain chemicals, or to mechanical stress, e.g. element movement caused by water hammer. Sometimes, O-rings have simply not been installed, or they have been improperly installed or moved out of their proper location during element loading.

b. Telescoping
FILMTEC elements can be mechanically damaged by an effect called telescoping, where the outer membrane layers of the element unravel and extend downstream past the remaining layers. A modest telescoping does not necessarily damage the membrane, but in more severe cases the glue line and/or the membrane can be ruptured.

Telescoping is caused by excessive pressure drop from feed to concentrate. Eight inch elements are more critical because of their greater feed side area. Make sure that a thrust ring is used with eight inch elements to support the elements' outer diameters. Elements with smaller diameter are supported by their permeate tubing.

The operating conditions that lead to excessive pressure drop are detailed in Section 9.4.3, High Differential Pressure.
Telescoping damage can be identified by probing and confirmed by a leak test (Section 9.3.2). Replace the damaged element(s) and correct the causes.

c. Membrane Surface Abrasion
This is not an individual element failure, but the front-end elements are typically most affected by crystalline or sharp-edged metallic suspended solids in the feed water. Check the incoming water for such particles. Microscopic inspection of the membrane surface will also reveal the damage. No corrective action is possible. The pretreatment must be changed to cope with this problem. Ensure that no particles are released from the high pressure piping. Afterwards all damaged membranes must be replaced.

d. Permeate Backpressure
When the permeate pressure exceeds the feed/concentrate pressure by more than 0.3 bar (5 PSI) at any time, the membrane may tear. The damage can be identified by probing. It is confirmed by the leak test (Section 9.3.2) and a visual inspection.

When a leaf of a backpressure damaged element is unrolled, the outer membrane typically shows creases parallel to the permeate tube, usually close to the outer glue line. The rupture of the membrane occurs mostly in the edges between the feed-sided glue line, the outer glue line, and the concentrate-sided glue line.

e. Centerfold Cracking
The FILMTEC® element designer includes one or more centerfolds of the membrane. These membrane creases run parallel to and close to the central product water tube. Although the folds are specially protected, the creased membrane can break under certain conditions. Then the salt passage increases, and the element shows a positive vacuum test result.

Centerfold cracking may have various causes:

- Hydraulic shock during start-up, e.g. by air in the system and/or too fast pressure increase. For the correct start-up procedure, see Section 6.2.
- Increased shear stress and/or abrasion by scaling and/or fouling.
- Permeate backpressure.

Centerfold cracking typically occurs only after one year or more of improper operation, and only at plants with a high start/stop frequency (see Section 6.3).

9.4.1.3 Low Permeate Flow

High salt passage combined with low permeate flow is the most commonly occurring condition for plant failure. Possible causes are:

a. Colloidal Fouling
Colloidal fouling occurs predominantly in the first array. The problem can more easily be localized when permeate flow meters have been installed in each array separately. Check SDI on a more regular basis to identify upset. Inspect SDI filters and cartridge filters for deposits. Clean the membranes (see cleaning instructions, Section 7) and correct the pretreatment accordingly.

b. Metal Oxide Fouling
Metal oxide fouling occurs predominantly in the first array. Check feedwater for levels of iron and aluminium. Check the materials of construction upstream of the membranes (see Section 4.13). Inspect SDI filters and cartridge filters for deposits. Clean the membranes (see cleaning instructions, Section 7) and analyze the spent cleaning solution for metals to identify cause. Correct the pretreatment and/or material selection.

c. Scaling
Scaling will involve deposits starting on the last array, and then gradually moving to the upstream arrays. Analyze the concentrate for levels of calcium, barium, strontium, sulfate, fluoride, silicate, pH and LSI (S&DSI for sea water). Try to calculate the mass balance for those salts, analyzing also feed water and permeate.

Scaling occurs typically very slowly because of the low concentrations involved ($CaCO_3$ and $CaSO_4$ scaling can also develop rapidly). The crystalline structure of the deposits can be observed under the microscope. The type of scaling is identified by a chemical analysis or X-ray analysis. Cleaning with acid and/or an alkaline EDTA solution with subsequent analysis of the spent solution may also help to identify the type of scalant.

In the case of carbonate scaling, adjust the pH of the pretreatment. For the other salts, either use an appropriate scale inhibitor or other suitable pretreatment techniques (see Section 3.3), or lower the recovery. Make sure that the design recovery is not exceeded, and the worst case feed water composition has been taken into account. Clean the membranes with a suitable chemical.

9.4.2
Low Permeate Flow

9.4.2.1 Normal Salt Passage

a. Biofouling
Biofouling of the membranes is indicated by the following changes in the operating parameters, predominantly at the front end of the system:

Permeate Flow:
decreases when operated at constant feed pressure and recovery.

Feed Flow:
decreases when operated at constant feed pressure and recovery, in cases where biofouling is advanced to large biomasses.

Feed Pressure:
has to be increased if the permeate flow is to be maintained at constant recovery. Increasing the feed pressure is however self-defeating when done for a long time, since it increases the fouling, making it more difficult to clean later.

Differential Pressure:
increases sharply when the bacterial fouling is massive or when it is combined with silt fouling.

Since pressure drop across the pressure vessels can be such a sensitive indicator of fouling, it is strongly recommended that provisions for installing pressure monitoring devices be included for each array in a system.

Salt Passage:
normal or even low at the beginning, increasing when fouling becomes massive.

High counts of microorganisms in water samples taken from the feed, concentrate, or permeate stream indicate the beginning or the presence of biofouling. For proper microbiological monitoring see Section 6.8 (Control of Microbiological Activity). When biofouling is suspected, the system should be checked according to the items described in Section 6.8.

Corrective measures include the installation or optimization of the pretreatment system to cope with the fouling potential of the raw water (see Section 3.6, Biological Fouling Prevention). In order to clean the membranes effectively it is important that the whole plant, including pretreatment, is disinfected. Chlorine can be used to disinfect the pretreatment line. Cleaning and disinfection of the membranes is described in Section 7. An incomplete cleaning and disinfection will result in rapid re-contamination.

b. Aged Preservation Solution
Elements or RO systems preserved in a bisulfite solution can also become biologically fouled, if the preservation solution is too old, too warm, or oxidized by oxygen. An alkaline cleaning usually helps to restore the permeate flow.

c. Incomplete Wetting
FILMTEC® elements that have been allowed to dry out, may have a too low permeate flow, because the fine pores of the polysulfone layer are not wetted. The techniques to re-wet dry membranes are described in Section 8.2.1.

9.4.2.2 Low Salt Passage

a. Compaction
Membrane compaction is typically associated with low permeate flow and improved salt rejection. Although the FT30 membrane shows little compaction when operated properly, significant compaction might occur under following conditions:

- high feed pressure
- high temperature
- water hammer

Water hammer can occur when the high pressure pump is started with air in the system.

Membrane compaction can be evidenced by a special membrane thickness measurement. Often, intrusions of the membrane into the permeate channel spacer fabric are visible. Thus, the permeate flow is not only restricted by the compaction of the polyamide or the polysulfone layer, but also by the reduced cross-section of the permeate spacer that is available for permeate flow.

Damaged elements must be replaced, or additional elements must be added at the tail-end of the system.

b. Organic Fouling
The adsorption of organic matter present in the feed water on the membrane surface causes flux loss, especially in the first array. In many cases, the adsorption layer acts as an additional barrier for dissolved salts, or plugs pinholes of the membrane, resulting in a lower salt passage. Organics with a high molecular mass and with hydrophobic or cationic groups can produce such an effect. Examples are oil traces or cationic polyelectrolytes, which are sometimes used in the pretreatment.

Analyse the incoming water for oil and organic matter, and check the SDI filter and the cartridge filter for organic deposits. Conduct SDI and TOC measurements on a more frequent basis. Improve the pretreatment accordingly (see Section 3.7, Prevention of Fouling by Organics).

An oil fouling can be removed with an alkaline cleaning agent, for example NaOH (pH 12) or Henkel P3-ultrasil 10.

Cationic polyelectrolytes may be cleaned off at an acidic pH, if it is not a precipitation product with other compounds, e.g. antiscalants.

Cleaning with alcohol has also proven effective in removing adsorbed organic films.

9.4.2.3 High Salt Passage

Low permeate flow in combination with high salt passage has already been discussed in Section 9.4.1.3. Whether the loss of permeate flow or the loss of salt rejection occurs first depends on the specific type of fouling/scaling layer and cannot be categorized.

9.4.3
High Differential Pressure

High differential pressure, also called pressure drop or Δp from feed to concentrate, causes a high force in flow direction on the feed side of the element. This force has to be taken by the permeate tubes and, in the case of 8" elements, by the fiberglass shells of adjacent elements in the same vessel. The stress on the last element in the vessel is the highest: it has to bear the sum of the forces created by the pressure drops of upstream elements.

The upper limit of the differential pressure per multi-element vessel is 4.1 bar (60 PSI), per single element 1.4 bar (20 PSI). When these limits are exceeded, even for a very short time, the FILMTEC® elements might be mechanically damaged. Elements smaller than 8" will become telescoped, and even the endcaps can be forced out of the wrapping.

Eight-inch elements will break at the weakest point of their fiberglass shell, which is where the endcap is connected to the roll. Luckily, the damage to the fiberglass shell does not normally affect the membrane performance. Even elements with membrane and feedspacer protruding out of the cracked shell have kept their good performance.

Although fiberglass cracking is, up to a certain degree, not more than a cosmetic problem, it does indicate that the differential pressure has been too high. This might have further implications such as flux loss or salt passage increase.

An increase in differential pressure at constant flow rates is usually due to the presence of debris, foulants, or scale within the element flow channels (feed spacer). It usually comes together with a decreasing permeate flow, and the causes for that have been discussed in Section 9.4.2.

An excessive pressure drop occurs when the recommended feed flow rates (Table 1 ot Section 4.1) are exceeded. It can also occur when the feed pressure builds up too fast during start-up (water hammer). The effect is dramatically increased with a foulant being present, especially a biofilm causes a high pressure drop.

Water hammer, a hydraulic shock to the membrane element, can also happen when the system is started up before all air has been flushed out. This could be the case at initial start-up or at operational start-ups, when the system has been allowed to drain. Ensure that the pressure vessels are not under vacuum when the plant is shut down (e.g. by installation of a vacuum breaker). In starting up a partially empty RO system, the pump may behave as if it had little or no backpressure. It will suck water at great velocities, thus hammering the elements. Also the high pressure pump can be damaged by cavitation.

The feed-to-concentrate differential pressure is a measure of the resistance to the hydraulic flow of water through the system. It is very dependent on the flowrates through the element flow channels and on the water temperature. It is therefore suggested that the permeate and concentrate flowrates be maintained as constant as possible in order to notice and monitor any element plugging that is causing an increase in differential pressure.

The knowledge of the extent and the location of the differential pressure increase provides a valuable tool to identify the cause(s) of a problem. Therefore it is useful to monitor the differential pressure across each array as well as the overall feed-to-concentrate differential pressure. Some of the common causes and prevention of high differential pressure are discussed below.

a. Bypass in Cartridge Filters

Cartridge filters have to protect the RO system from large debris that can physically block the flow channels in the lead-end elements. Such blocking can happen when cartridge filters are loosely installed in their housing, connected without using interconnectors, or completely forgotten.

Sometimes cartridge filters will deteriorate while in operation due to hydraulic shock or the presence of incompatible materials. Cellulose-based filters should be avoided, because they may deteriorate and plug the FILMTEC elements.

b. Pretreatment Media Filter Breakthrough

Occasionally, some of the finer media from sand, multimedia, carbon, weak acid cation exchange resin, or diatomaceous earth pretreatment filters may break through into the RO feedwater. Cartridge filters should catch most of the larger particles; but certain types of fine media, such as carbon fines and diatomaceous earth, can pass right through a five micron nominally rated cartridge filter and physically plug the lead elements.

Chemical cleaning is difficult, it can be tried to rinse out the deposits with detergents. Separate single-element cleaning is recommended to avoid the transport of removed particles into other elements. Diatomaceous earth filters should be taken off-line when such problems are encountered. Soft carbons made from coal should be replaced by coconut-shell-based carbons with a hardness rating of 95 or better. New media should be sufficiently backwashed to remove fines before the bed is put into service.

c. Pump Impeller Deterioration
Most of the multistage centrifugal pumps employ at least one plastic impeller. When a pump problem such as misalignment of the pump shaft develops, the impellers have been known to deteriorate and throw off small plastic shavings. The shavings can enter and physically plug the lead-end RO elements.

It is suggested that the discharge pressure of RO pumps be monitored before any control valves as part of a routine maintenance schedule to see if the pump is maintaining its output pressure. If not, it may be deteriorating.

d. Scaling
Scaling can cause the tail-end differential pressure to increase. Make sure that scale control is properly taken into account (see Section 3.3), and clean the membranes with the appropriate chemicals (see Section 7.6). Ensure that the designed system recovery will not be exceeded.

e. Brine Seal Damage
Brine seal damage can cause a random increase in differential pressure. Brine seals can be damaged or “turned over” during installation or due to hydraulic surges. This results in a certain amount of feedwater bypass around the element and less flow and velocity through the element, thus exceeding the limit for maximum element recovery. When this occurs, the element is more prone to fouling and scaling. As a fouled element in one of several multi-element pressure vessels becomes more plugged, there is a greater tendency for the downstream elements to become fouled due to insufficient concentrate flow rates within that vessel.

f. Biological Fouling
Biological fouling is typically associated with a marked increase of the differential pressure at the lead end of the RO system. Biofilms are gelatinous and quite thick, thus creating a high flow resistance. Corrective measures have been described in Section 9.4.2.1.

g. Precipitated Antiscalants
When polymeric organic antiscalants come into contact with multivalent cations like aluminium; or with residual cationic polymeric flocculants, they will form gumlike precipitants which can heavily foul the lead elements. Cleaning will be difficult; repeated application of an alkaline EDTA solution may help.

9.4.4
Overview

Changes of the permeate flow, the salt passage, and the differential pressure are symptoms which can be attached to specific causes in many cases. Although, the symptoms of different causes may overlap in reality, and the symptoms are more or less pronounced in specific cases. An overview of symptoms, their possible causes and corrective measures are given in Table 1.

Table 1: Symptoms, Causes and Corrective Measures

Permeate Flow	Salt Passage	Different. Pressure	Direct Cause	Indirect Cause	Corrective Measure
↑	⇑	→	Oxidation Damage	Free Chlorine, Ozone, $KMnO_4$	Replace Element
↑	⇑	→	Membrane Leak	Permeate Backpressure; Abrasion	Replace Element; Improve Cartridge Filtration
↑	⇑	→	O-Ring Leak	Improper Installation	Replace O-Ring
↑	⇑	→	Leaking Product Tube	Damaged During Element Loading	Replace Element
⇓	↑	↑	Scaling	Insufficient Scale Control	Cleaning; Scale Control
⇓	↑	↑	Colloidal Fouling	Insufficient Pretreatment	Cleaning, Improve Pretreatment
↓	→	⇑	Biofouling	Contaminated Raw Water, Insufficient Pretreatment	Cleaning, Disinfection Improve Pretreatment
⇓	→	→	Organic Fouling	Oil; Cationic Polyelectrolytes	Cleaning, Improve Pretreatment
⇓	↓	→	Compaction	Water Hammer	Replace Element or Add Elements

↑ increasing ↓ decreasing → not changing ⇑ main symptom

9.5 References

(1) Bukay, M.; Byrne, W.: RO Troubleshooting

Pt. 1: Ultrapure Water, March/April 1986, 58-62
Pt. 2: Ultrapure Water, May/June 1986, 59-62
Pt. 3: Ultrapure Water, July/August 1986, 59-62
Pt. 4: Ultrapure Water, Sept./Oct. 1986, 58-62
Pt. 5: Ultrapure Water, Nov./Dec. 1986, 56-60

(2) ASTM D3923-80 (Reapproved 1989):
Standard Practices for Detecting Leaks in Reverse Osmosis Devices

(3) ASTM D4194-89:
Standard Test Methods for Operating Characteristics of Reverse Osmosis Devices

10. Addendum

10.1 Terminology

A-value:	Membrane water permeability coefficient.
Array:	Series of parallel installed pressure vessels with common feed, product and reject lines.
B-value:	Salt diffusion coefficient.
Bank:	See *RO train*.
Boundary layer:	Layer adhering to the membrane facing the feed/concentrate water.
Brine:	See *Concentrate*.
CAC:	Combined Available Chlorine.
CIP:	Cleaning-in-place.
CRC:	Combined Residual Chlorine.
Composite membrane:	Membrane obtained precipitating a thin desalinating layer on a porous carrier membrane.
Concentrate:	The remaining solution with the retained salts (also called retentate, or brine, or reject).
Concentration Factor:	CF is the ratio of the feed quantity (or feed stream) over the concentrate quantity (or concentrate stream).
Concentration polarization:	Increase of solute concentration in *Boundary layer*.
Double pass RO system:	RO system in which the permeate is further desalinated by a subsequent RO system.
FAC:	Free Available Chlorine.
FRC:	Free Residual Chlorine.
Feed:	The liquid entering the module.
Fouling:	The deposition of foreign matter on the membrane surface, resulting in changed element performance.
GAC:	Granular Activated Carbon.
LSI:	Langelier Saturation Index.
Membrane configuration:	The arrangement of individual elements in the RO plant.
Membrane salt passage:	SP_M is the concentration of a compound in the permeate related to its average concentration on the feed/concentrate side.
Module:	Pressure vessel containing membrane element(s).
Molality:	The number of gram-molecules weight of a solute per kg of solvent.
Molarity:	The number of gram-molecules weight of a solute per l of solution.
OEM:	Original equipment manufacturer.

Permeate:	The portion of the feed which passes through the membrane, also called product.
Permeate channel spacer:	Fabric that mechanically supports the membrane and drains the permeate to the permeate tube.
Permeate collector fabric:	See *Permeate channel spacer*.
Permeate flux:	Permeate flow rate per unit membrane area, expressed communly as l/m^2 h (or GFD)
Plant capacity:	Production of permeate per unit time, expressed as m^3/day or m^3/h (GPD, MGD).
Pressure vessel:	The vessel containing the individual elements.
Product water:	See *Permeate*.
Raw water:	Untreated water from wells, surface sources or the sea.
Recovery:	Y is the ratio of product quantity (or product stream) over the feed quantity (or feed stream), given as fraction or in percent.
Reject:	See *Concentrate*.
Rejection:	The ability of the membrane to hinder certain elements from passing through. Expressed as 1 minus the ratio between the concentration in the product and the feed.
Reverse Osmosis:	A pressure driven membrane operation in which the solvent is transferred through the membrane and the dissolved solutes are retained by the same membrane.
Retentate:	See *Concentrate*.
RO train:	One of two or more complete RO installations operating in parallel.
SBS:	Sodium bisulfite.
SDI:	Silt Density Index.
S&DSI:	Stiff and Davis Saturation Index.
SHMP:	Sodium hexametaphosphate.
SMBS:	Sodium meta bisulfite.
Scaling:	Deposition of solids on the membrane surface, due to exceeding the solubility product of the salt in question.
System salt passage:	SP_s is the concentration of a compound in the permeate related to its concentration in the feed water, also called apparent salt passage.
TBC:	Total Bacteria Count.
TDS:	Total dissolved solids, usually expressed as mg/l or ppm (parts per million).
TOC:	Total organic carbon.
TRC:	Total Residual Chlorine.
TSS:	Total suspended solids.
Telescoping:	Lengthwise displacement of the membrane inside the RO element.

10.2 Specific Conductance of Sodium Chloride

µmhos/cm	ppm	µmhos/cm	ppm	µmhos/cm	ppm
10	5	500	247	990	495
20	9	510	252	1000	500
30	14	520	257	1020	510
40	19	530	262	1040	520
60	28	550	272	1080	540
70	33	560	277	1100	550
80	38	570	282	1120	561
90	42	580	287	1140	571
100	47	590	292	1160	581
110	52	600	297	1180	591
120	57	610	302	1200	601
130	61	620	307	1220	611
140	66	630	312	1240	621
150	71	640	317	1260	632
160	75	650	323	1280	642
170	80	660	328	1300	652
180	85	670	333	1320	662
190	90	680	338	1340	672
200	95	690	343	1360	682
210	100	700	348	1380	692
220	105	710	353	1400	702
230	110	720	358	1420	713
240	115	730	363	1440	723
250	120	740	368	1460	733
260	125	750	373	1480	743
270	130	760	378	1500	754
280	135	770	383	1525	766
290	140	780	388	1550	770
300	145	790	393	1575	792
310	150	800	399	1600	805
320	155	810	404	1625	817
330	160	820	409	1650	830
340	165	830	414	1675	843
350	171	840	419	1700	856
360	176	850	424	1725	868
370	181	860	429	1750	881
380	186	870	434	1775	894
390	191	880	439	1800	907
400	196	890	444	1825	920
410	201	900	449	1850	932
420	206	910	454	1875	945
430	211	920	459	1900	958
440	216	930	464	1925	971
450	221	940	469	1950	983
460	226	950	474	1975	996
470	231	960	480	2000	1000
480	236	970	485	2025	1022
490	241	980	490	2050	1034

µmhos/cm	ppm	µmhos/cm	ppm	µmhos/cm	ppm
2075	1047	4100	2136	8800	4767
2125	1073	4200	2191	8900	4823
2150	1085	4300	2245	9000	4879
2175	1098	4400	2300	9100	4935
2200	1111	4500	2356	9200	4991
2225	1124	4600	2412	9216	5000
2250	1137	4700	2468	9300	5047
2275	1140	4800	2524	9400	5103
2300	1162	4900	2580	9500	5159
2325	1175	5000	2636	9600	5215
2350	1188	5100	2692	9700	5271
2375	1200	5200	2748	9800	5327
2400	1213	5300	2805	9900	5383
2425	1226	5400	2861	10000	5439
2450	1239	5500	2917	10200	5551
2475	1251	5600	2973	10400	5664
2500	1264	5700	3029	10600	5776
2550	1290	5800	3085	10800	5888
2600	1315	5900	3141	11000	6000
2650	1344	6000	3197	11200	6122
2700	1371	6100	3253	11400	6243
2750	1398	6200	3309	11600	6364
2800	1426	6300	3365	11800	6485
2850	1453	6400	3421	12000	6607
2900	1480	6500	3477	12200	6728
2950	1508	6600	3533	12400	6843
3000	1535	6700	3589	12600	6970
3050	1562	6800	3645	12800	7091
3100	1589	6900	3701	13000	7213
3150	1617	7000	3758	13200	7334
3200	1644	7100	3814	13400	7455
3250	1671	7200	3870	13600	7576
3300	1699	7300	3926	13800	7898
3350	1726	7400	3982	14000	7819
3400	1753	7500	4038	14200	7940
3450	1781	7600	4094	14400	8061
3500	1808	7700	4150	14600	8182
3550	1835	7800	4206	14800	8304
3600	1863	7900	4262	15000	8425
3650	1899	8000	4318	15250	8576
3700	1917	8100	4374	15500	8728
3750	1945	8200	4430	15750	8879
3800	1972	8300	4486	16000	9031
3850	1999	8400	4542	16250	9182
3900	2027	8500	4598	16500	9334
3950	2054	8600	4654	16750	9486
4000	2081	8700	4710	17000	9637

10.2 Specific Conductance of Sodium Chloride

µmhos/cm	ppm	µmhos/cm	ppm	µmhos/cm	ppm
17500	9940	34000	20084	76000	48053
17750	10092	34500	20391	77000	48731
18000	10247	35000	20698	78000	49409
18250	10400	35500	21006	79000	50087
18500	10554	36000	21313	80000	50765
18750	10708	36500	21621	81000	51443
19000	10852	37000	21928	82000	52121
19250	11015	37500	22235	83000	52799
19500	11169	38000	22543	84000	53477
19750	11323	38500	22850	85000	54155
20000	11476	39000	23158	86000	54833
20250	11630	39500	23465	87000	55511
20500	11784	40000	23773	88000	56130
20750	11937	41000	24387	89000	56867
21000	12091	42000	25002	90000	57545
21250	12245	43000	25679	91000	58223
21500	12399	44000	26357	92000	58901
21750	12552	45000	27035	93000	59579
22000	12705	46000	27713	94000	60257
22250	12860	47000	28391	95000	60935
22500	13013	48000	29069	96000	61613
22750	13167	49000	29747	97000	62291
23000	13321	50000	30425	98000	62969
23250	13474	51000	31103	99000	63647
23500	13628	52000	31781	100000	64325
23750	13782	53000	32459		
24000	13936	54000	33137		
24250	14089	55000	33815		
24500	14243	56000	34493		
24750	14397	57000	35171		
25000	14550	58000	35849		
25500	14858	59000	36527		
26000	15165	60000	37205		
26500	15473	61000	37883		
27000	15780	62000	38561		
27500	16087	63000	39239		
28000	16395	64000	39917		
28500	16702	65000	40595		
29000	17010	66000	41273		
29500	17317	67000	41961		
30000	17624	68000	42629		
30500	17932	69000	43307		
31000	18239	70000	43985		
31500	18547	71000	44663		
32000	18854	72000	45341		
32500	19161	73000	46091		
33000	19469	74000	46697		

10.3 Conductivity of Ions Expressed as µS/cm per meq/l, Infinitely Diluted

Ion	20°C (68°F)	25°C (77°F)	100°C (212°F)
H^+	328	350	646
Na^+	45	50.1	155
K^+	67	73.5	200
NH_4^+	67	73.5	200
Mg^{++}	47	53.1	170
Ca^{++}	53.7	59.5	191
OH^-	179	197	446
Cl^-	69.0	76.3	207
HCO_3	36.5	44.5	-
NO_3^-	65.2	71.4	178
$H_2PO_4^-$	30.1	36.0	-
CO_3^{--}	63.0	72.0	-
HPO_4^{--}	-	53.4	-
SO_4^{--}	71.8	79.8	234
PO_4^{---}	-	69.0	-

Source: Landolf-Börnstein 6° edition Band II/7

10.4 Conductivity of Solutions, Acids, Alkalies and Salts 25°C Expressed as µS/cm per meq/l

Component	Concentration in meq/l							
	Infin. Diluted	0.1	0.5	1.0	5.0	10.0	50.0	100.0
HCl	426	425	423	421	415	412	399	392
HNO_3	421	420	417	416	410	407	394	386
H_2SO_4	430	424	412	407	390	380	346	317
H_3PO_4	419	394	359	336	264	223	133	104
NaOH	248	247	246	245	241	238	227	221
KOH	271	270	269	268	264	261	251	246
NH_4OH	271	109	49	36	17	12	5.6	3.9
NaCl	126	126	124	124	121	118	111	107
Na_2SO_4	130	128	126	124	117	113	97.7	90.0
Na_2CO_3	124	122	120	119	112	108	93.2	86.3
$NaHCO_3$	96.0	95.2	94.2	93.5	90.5	88.4	80.6	76.0
KCl	150	149	148	141	144	141	133	129

Source: Landolt Börnstein 6° edition Band II/7

The graph below and the graph on the following page relate the conductivity of a solution containing one given chemical to the concentration of this chemical.

The conductivity of solutions at other temperatures can be calculated by multiplying conductivities at 25°C (77°F) with the correction factors in the following table. These factors are only valid for diluted solutions as they presuppose total ionic dissociation of the chemical.

Table 1: Conductivity correction factors

	0°C (32°F)	18 (64°F)	25 (77°F)	50°C (122°F)
HCl	0.66	0.89	1.00	1.37
H_2SO_4	0.66	0.87	1.00	1.38
NaCl	0.53	0.86	1.00	1.57
NaOH	0.54	0.89	1.00	1.51
KOH	0.55	0.89	1.00	1.50

Figure 1: Conductivity of Ionic Solutions at 25°C (77°F)

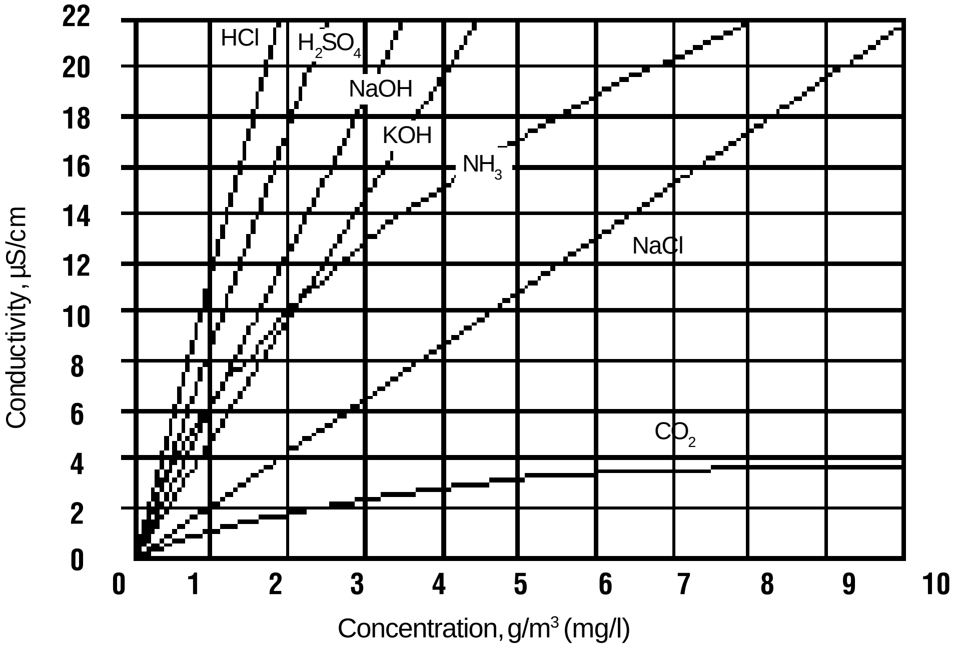
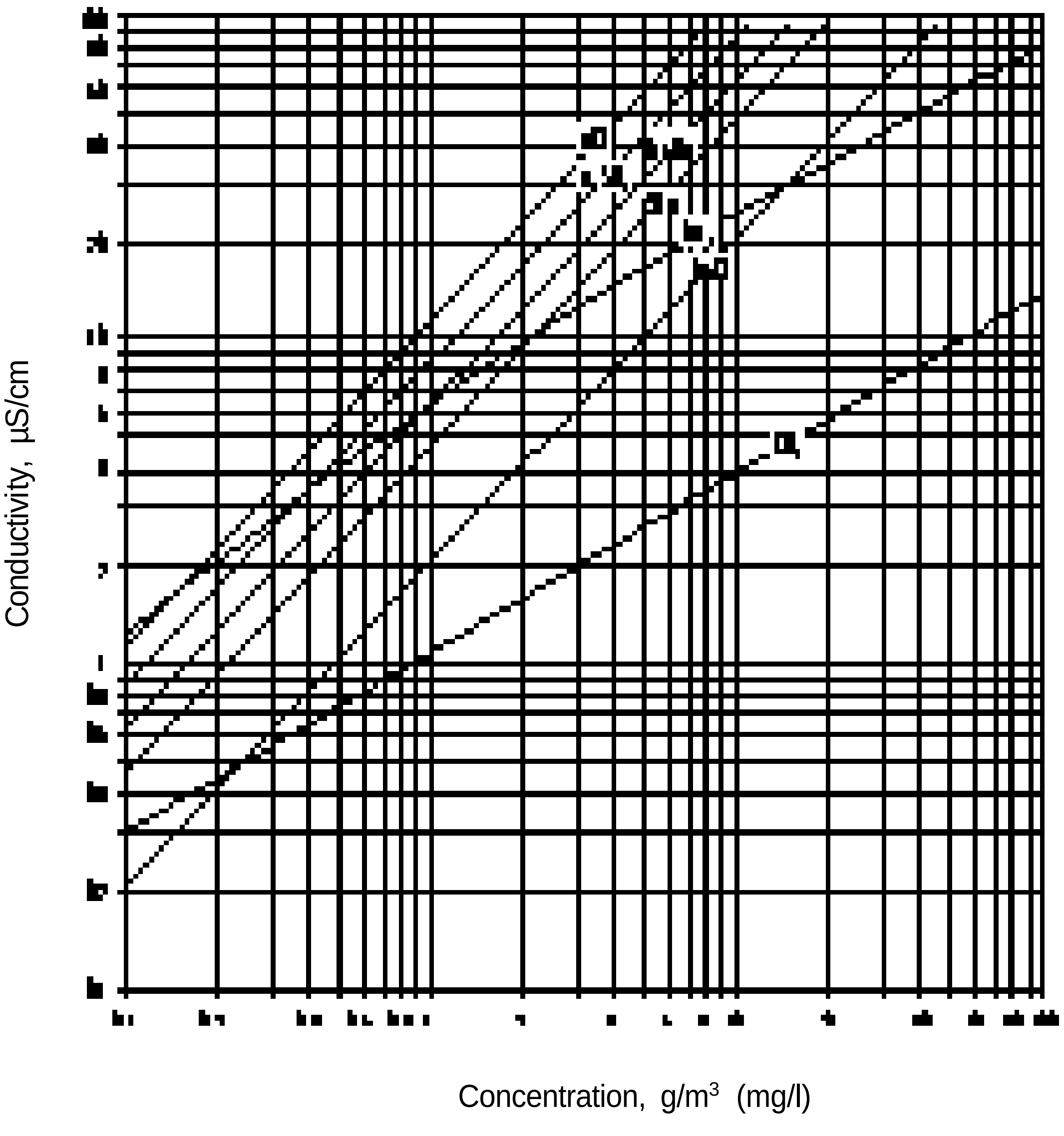


Figure 2: Conductivity of Ionic Solutions at 25°C (77°F)



10.5 Conversion of Concentration Units of Ionic Species

The following table gives conversion factors for the conversion of concentration units of ionic species given as gram of the ion per liter (g/l) into equivalent per liter (eq/l) or of gram of $CaCO_3$ equivalents per liter (g $CaCO_3$/l).

Compound	Formula	Ionic Weight	Equiv. Weight	Conversion to	
				g $CaCO_3$/l	eq/l
Positive Ions					
Aluminium	Al^{+++}	27.0	9.0	5.56	0.111
Ammonium	NH_4^+	18.0	18.0	2.78	0.0556
Barium	Ba^{++}	137.4	68.7	0.73	0.0146
Calcium	Ca^{++}	40.1	20.0	2.50	0.0500
Copper	Cu^{++}	63.6	31.8	1.57	0.0314
Hydrogen	H^+	1.0	1.0	50.0	1.0000
Ferrous Iron	Fe^{++}	55.8	27.9	1.79	0.0358
Ferric Iron	Fe^{+++}	55.8	18.6	2.69	0.0538
Magnesium	Mg^{++}	24.3	12.2	4.10	0.0820
Manganese	Mn^{++}	54.9	27.5	1.82	0.0364
Potassium	K^+	39.1	39.1	1.28	0.0256
Sodium	Na^+	23.0	23.0	2.18	0.0435
Negative Ions					
Bicarbonate	HCO_3^-	61.0	61.0	0.82	0.0164
Carbonate	CO_3^{--}	60.0	30.0	1.67	0.0333
Chloride	Cl^-	35.5	35.5	1.41	0.0282
Fluoride	F^-	19.0	19.0	2.63	0.0526
Iodide	I^-	126.9	126.9	0.39	0.0079
Hydroxide	OH^-	17.0	17.0	2.94	0.0588
Nitrate	NO_3^-	62.0	62.0	0.81	0.0161
Phosphate (tri-basic)	PO_4^{---}	95.0	31.7	1.58	0.0315
Phosphate (di-basic)	HPO_4^{--}	96.0	48.0	1.04	0.0208
Phosphate (mono-basic)	$H_2PO_4^-$	97.0	97.0	0.52	0.0103
Sulfate	SO_4^{--}	96.1	48.0	1.04	0.0208
Bisulfate	HSO_4^-	97.1	97.1	0.52	0.0103
Sulfite	SO_3^{--}	80.1	40.0	1.25	0.0250
Bisulfite	HSO_3^-	81.1	81.1	0.62	0.0123
Sulfide	S^{--}	32.1	16.0	3.13	0.0625
Neutral [1]					
Carbondioxide	CO_2	44.0	44.0	1.14	0.0227
Silica	SiO_2	60.0	60.0	0.83	0.0167
Ammonia	NH_3	17.0	17.0	2.94	0.0588

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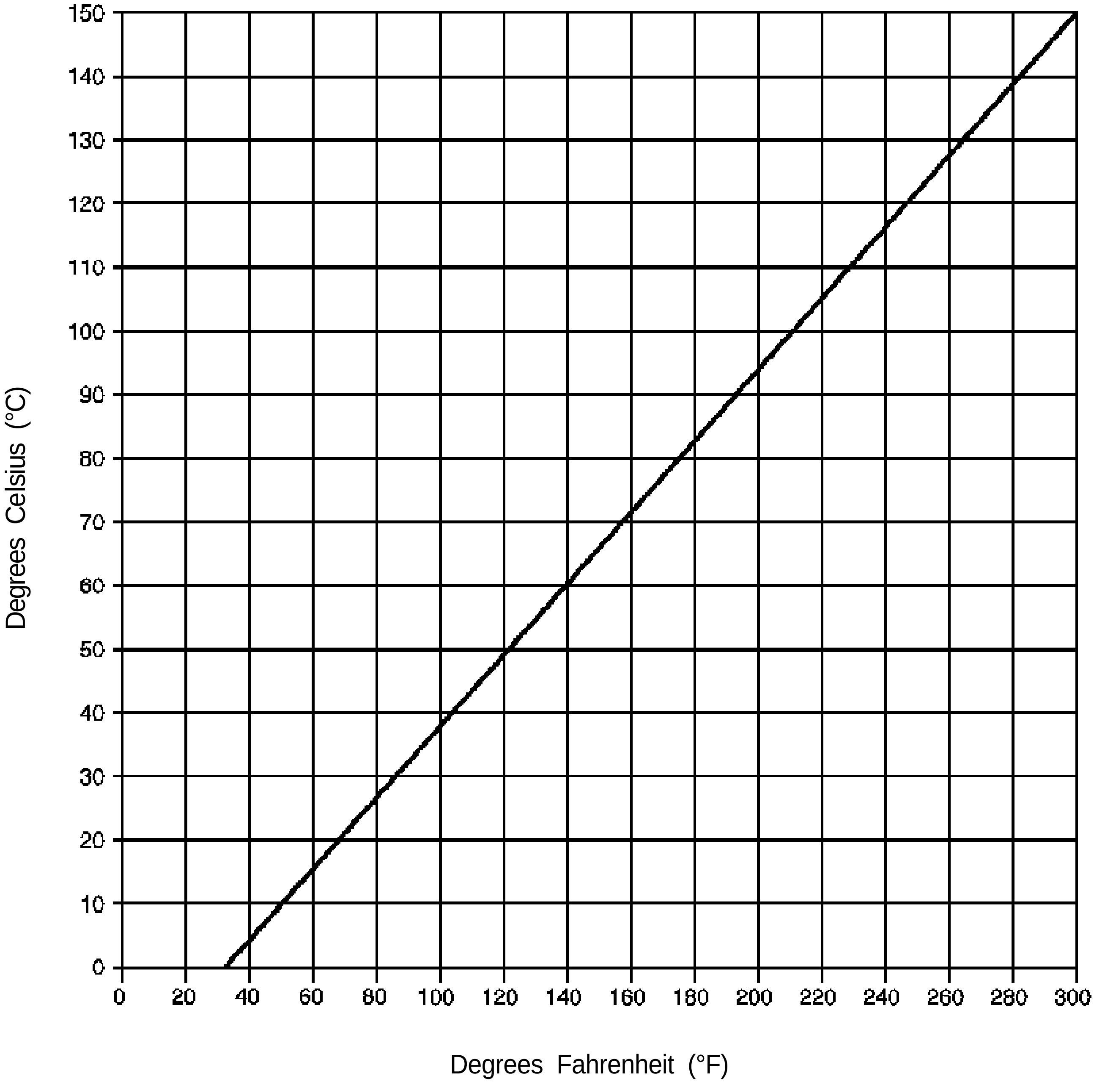
[1] Calculations based on conversion to monovalent species

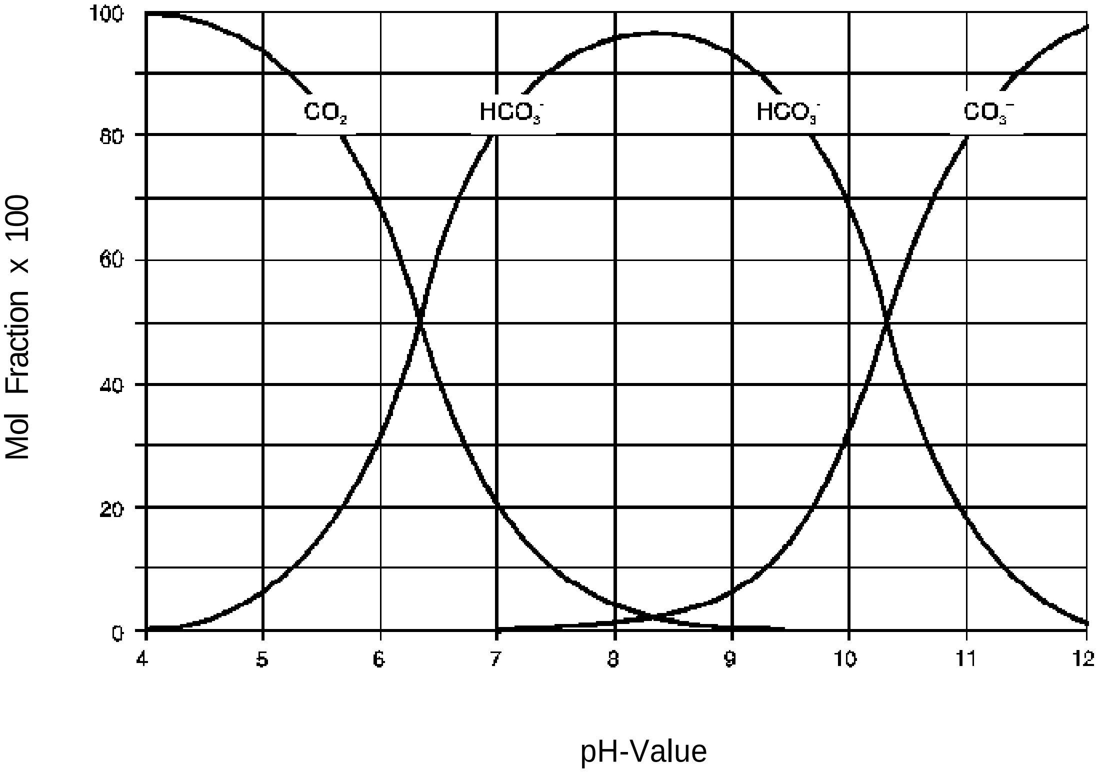
10.6 Conversion of Temperature Units



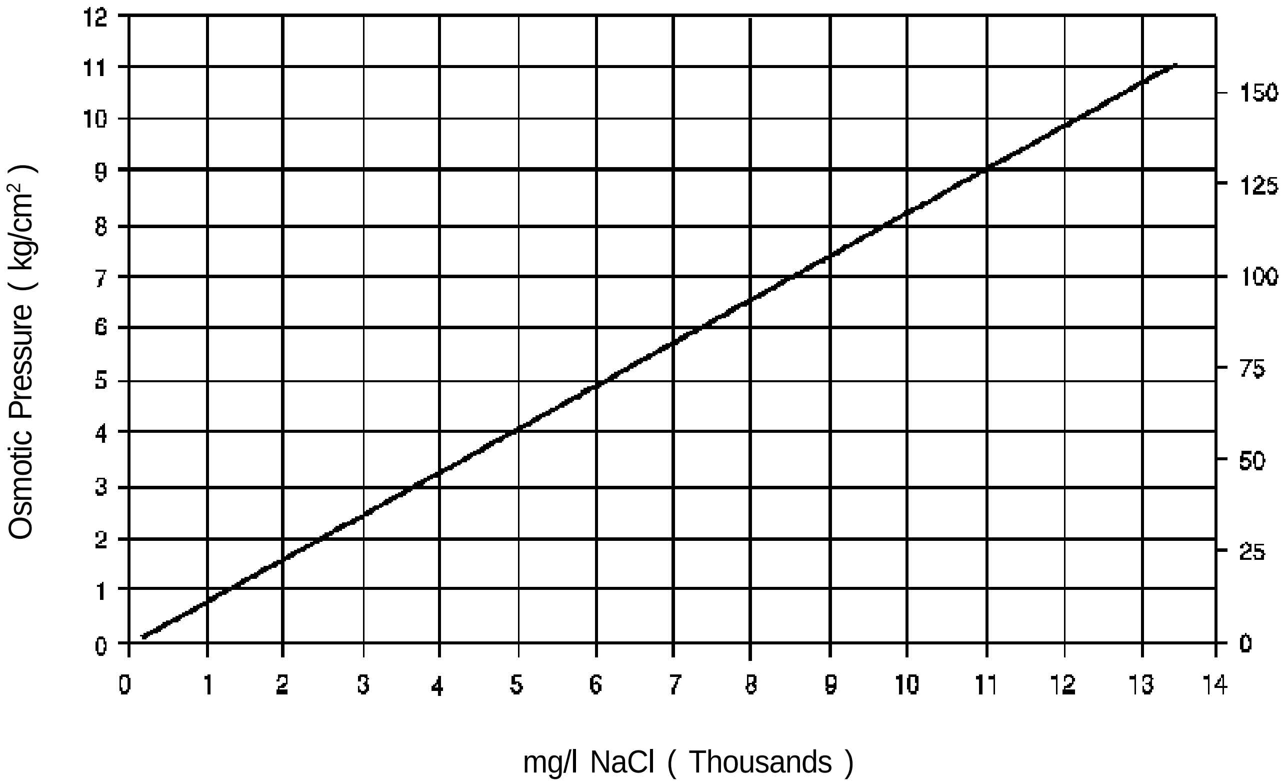
10.7 Conversion of U.S. Units into Metric Units

1 Inch (in.) = 2.54 cm	=	0.0254	m
1 Foot (ft.)	=	0.3048	m
1 Square Foot (sq. ft.)	=	0.0929	m^2
1 Gallon (US)	=	3.785	l
1 Pound per sq. in. (PSI)	=	0.069	bar
1 Gallon per minute (GPM)	=	0.227	m^3/h
	=	0.063	l/s
1 Gallon per day (GPD)	=	0.003785	m^3/d
	=	0.158	l/h
1 Million Gallons per day (MGD)	=	157.73	m^3/h
	=	3785	m^3/d
1 Gallon per sq. ft. and day (GPD)	=	1.70	l/m^2h

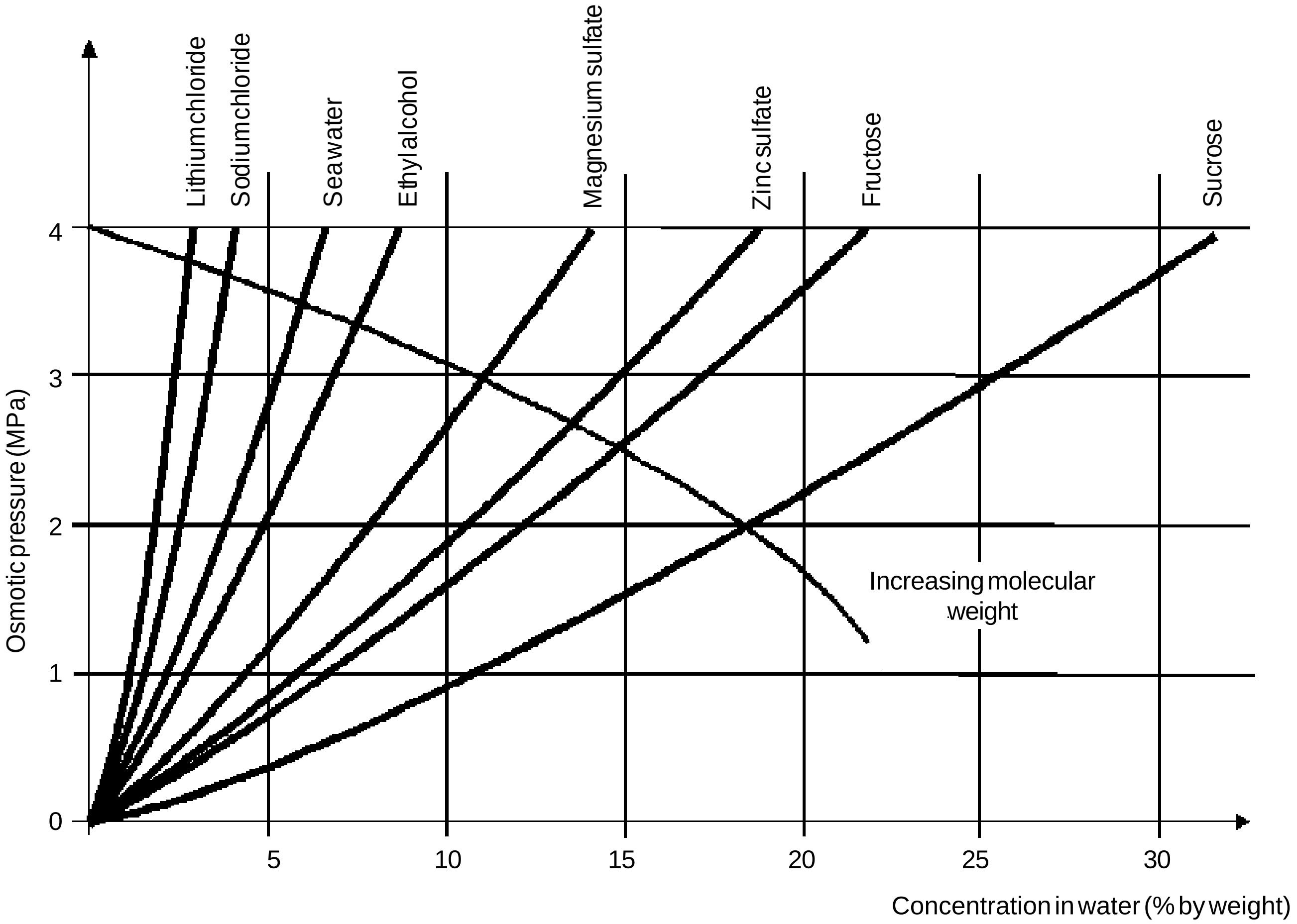
10.8 Ionization of Carbon Dioxide Solutions as Function of the pH at 25°C (77°F)



10.9 Osmotic Pressure of Sodium Chloride



10.10 Osmotic Pressure of Solutions



10.11 Chemical Compatibility Process for Reverse Osmosis and Nanofiltration Membranes Used in Water Treatment

Introduction

Inorganic and organic chemicals are used in the operation of reverse osmosis (RO) and nanofiltration (NF) systems to control water chemistry prior to, and at, the membranes. Chemicals are also used for cleaning, sanitizing, and storage of elements and systems on a periodic basis. It is important that chemicals used in these operations are compatible with the membranes so that their performance and effective operating life can be optimized.

The types of chemicals covered by the chemical compatibility process are scale inhibitors (antiscalants/ dispersants), cleaning chemicals, biocides, and membrane preservatives (storage solutions). The Dow Chemical Company and FilmTec Corporation do not judge products on their efficacy.

Coagulants, polyelectrolytes, and other pretreatment polymers are not covered by this process. These products react with suspended and colloidal matter in water to form an end-product which cannot be judged by chemical compatibility testing.

The Dow Chemical Company and FilmTec Corporation do not perform compatibility tests on products seeking recognition as "compatible" chemicals for use with our membrane. This is the responsibility of the manufacturer or supplier of the product. We have developed detailed test protocols and criteria for evaluating test results which should be used to detemine the compatibility of a product with our RO and NF membrane elements. Technical Service and Develompment (TS&D) personnel can answer any questions about these protocols.

Compatibility Testing Process

The process for judging if a chemical is compatible with our membrane products is as follows:

1. Contact field sales or technical service and development (TS&D) representative with information about the chemical. This should include material safety data sheets (MSDS), literature detailing use and operation of the product, and safety concerns (if any) when using the product.
2. The chemical manufacturer or supplier will perform compatibility testing per the test protocol.
3. Data from the compatibiltiy tests are submitted to TS&D for review and analysis. The results of the test will be compared with the evaluation criteria in determining compatibility.
4. If the chemical is judged as compatible, then a letter will be provided to the chemical manufacturer or supplier which states that the chemical has successfully passed the chemical compatibility test. If the formulation of the chemical changes, then compatibility testing will need to be repeated.

Compatibilty Testing of Antiscalants and Biocides

An antiscalant can negatively interfere with the membrane in two ways, either directly or by promoting microbiological growth. In addition to the compatibility test outlined below tests should be conducted to ensure that the antiscalant will remain microbiologically inactive during long term storage conditions.

For an antiscalant or biocide to be considered compatible for use with FILMTEC membranes, a 1000 hour test must be carried out. The test can be conducted at the chemical manufacturer's laboratory, a special test facility or at an existing RO unit in operation with FILMTEC® membranes.

In order to establish the baseline, the system shall be in operation for at least 12 hours without chemical injection. The test will not be considered valid if the permeate flow rate is more than 15 percent below the expected value for clean membrane.

After the baseline is established, the chemical is then added continuously for at least 1000 hours. The normalized permeate flow and salt passage should remain relatively constant during this time for the chemical to be deemed compatible. The upper concentration limit for compatiblity will be the maximum concentration of the chemical in the concentrate stream.

Compatibility Testing of Cleaning Chemicals

A cleaning chemical is considered compatile with a FILMTEC membrane if a two hour cleaning does not lower the membrane flux or salt rejection, and a two week soak test does not lower the salt rejection.

The salt used for performance test of the membrane is sodium chloride for the FT30 membrane and magnesium sulfate for NF membranes. The tests can be carried out at the cleaning chemical manufacturer's laboratory or any other reputable laboratory.

Two Hour Cleaning Test

1. Test the membrane at standard BW test conditions. [225 psig (1.6 MPa), 77° F (25 °C) and 2000 ppm sodium chloride]
2. Clean with double the normal strength of the cleaning solution by circulating the solution over the membrane at recommended cleaning temperature and 50 psig for two hours.
3. Rinse out cleaning solution. Use low conductivity water for this to be able to check that both permeate side and brine side of the membrane have been rinsed out effectively.
4. Retest at BW test conditions according to point 1 above. Flux loss shall be less than five percent and there shall be no increase in salt passage compared to the initial test in point 1 above.

Two Week Soak in Cleaning Solution

1. Test the membrane at standard BW test conditions. [225 psig (1.6 MPa), 77° F (25 °C) and 2000 ppm sodium chloride]
2. Soak the membrane in normal strength cleaning solution at normal cleaning temperature for two weeks.
3. Rinse out cleaning solution. Use low conductivity water for this to be able to check that both permeate side and brine side of the membrane have been rinsed out effectively.
4. Retest at BW test conditions according to point 1 above. There shall be no increase in salt passage compared to the initial test in point 1 above.