Advanced Water Treatment
(DESALINATION)

EEENV 5330 معالجة مياه متقدمة

PART 6 : RO SEPARATION

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RO Separation Systems

14.1 Introduction

- This part an **overview of the key components and configuration of membrane systems for brackish and seawater desalination applying spiral-wound polyamide thin-film composite reverse osmosis (RO) membrane elements (modules),** which are the most commonly used type of reverse osmosis separation systems at present.

- Figure 14.1 depicts a typical configuration of RO system.

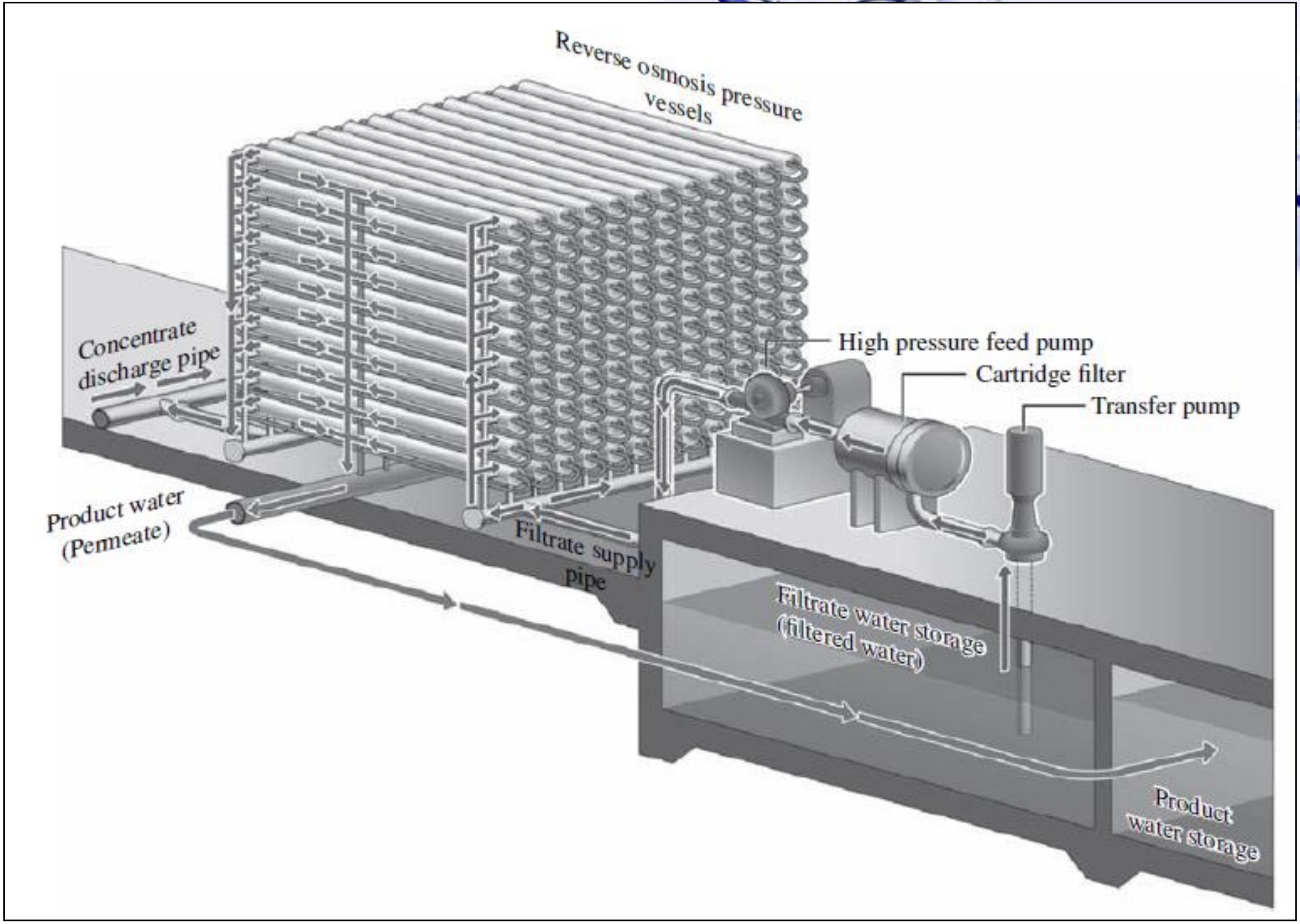

Figure 14.1 General RO membrane system configuration.

14.1 Introduction

- The filtered water produced by the plant's pretreatment system is conveyed by transfer pumps from a filtrated water storage tank through cartridge filters and **into the suction pipe of the high pressure RO feed pumps, which, in turn, deliver this water to the RO pressure vessels that contain the membrane elements where the actual desalination process occurs**.

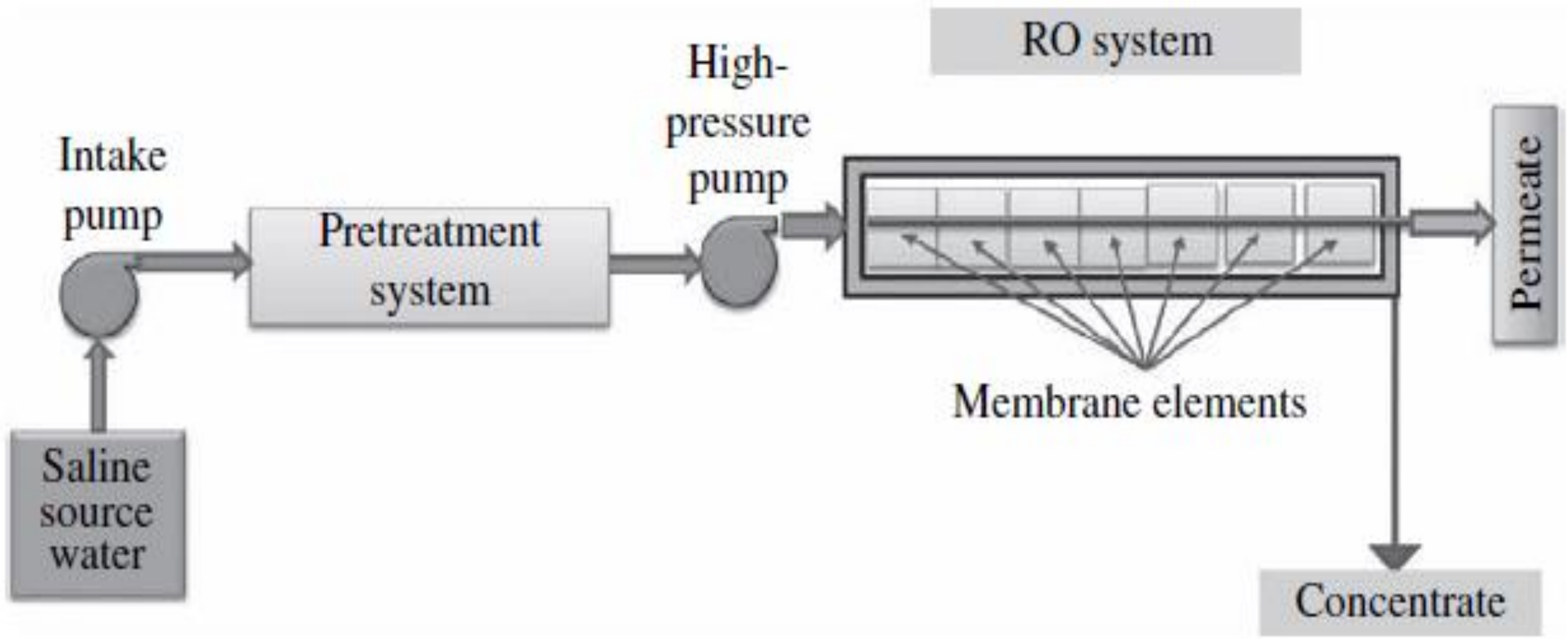

Figure 14.2 Direct flow-through desalination system.

14.4 Spiral- Wound Polyamide Membrane Elements

- Spiral-wound RO membrane elements could be classified in three main categories by the type of water they are configured and designed to desalinate:

1. nanofiltration (water softening) (NF) elements.
2. brackish water desalination (BWRO) elements.
3. seawater (SWRO) membrane elements.

Performance Parameter	Type of Membrane Element		
	NF	BWRO	SWRO
Typical source water salinity range, mg/L	400–1000	800–10,000	15,000–47,000
Operating feed pressure bars (lb/in^2)	5–8 (70–120)	10–15 (150–220)	55–70 (800–1000)
Average flux rate, Lmh (gfd)	20–40 (12–24)	20–40 (12–24)	14–16 (8–9.4)
Specific flux rate, Lmh/bar ($gfd/lb/in^2$)	3.5–7.0 (0.17–0.34)	2.0–4.0 (0.08–0.16)	1.0–1.5 (0.04–0.06)
Nominal salt rejection, %	70.0–95.0	99.0–99.7	99.5–99.8
Average product water flow rate per element, m^3/day (gpd)	20–25 (5000–6600)	20–25 (5000–6600)	12–15 (3200–4000)

Table 14.1 Key Performance Parameters of NF, BWRO, and SWRO Membrane Elements

14.4.3 Brackish Water Desalination Elements

- BWRO elements are designed to treat source waters of salinity above 500 mg/L and as high as 10,000 to 15,000 mg/L. As shown in Table 14.1, **their optimal operation range is typically up to 10,000 mg/L**.

- Depending on their key performance parameters, brackish water reverse osmosis elements can be subdivided in the following main groups:

  1. high-rejection membranes.
  2. low-energy membranes.
  3. low-fouling membranes.
  4. high-productivity membranes.

14.4.3 Brackish Water Desalination Elements

- High-Rejection BWRO Membranes

- This type of membrane has several-tenths of a percent higher rejection (i.e., **99.5 to 99.7 percent**) than standard BWRO elements, which reject 99.0 to 99.3 percent of the salts in the source water.

- Low-Energy BWRO Membranes

- These membrane elements are designed to produce approximately the same volume of water but at lower feed pressure (i.e., **higher specific flux**).

Parameter	Commercial Membrane Element Model ESPA 2+ Hydranautics	 BW30-400 Dow Filmtec	 TM720-400 Toray
Product water flow rate, m^3/day (gpd)	41.6 (11,000)	40.0 (10,500)	39 (10,200)
Nominal NaCl rejection, %	99.6	99.5	99.7
Test feed pressure, bars (lb/in^2)	10.3 (150)	15.8 (225)	15.8 (225)
Specific Flux, Lmh/bar (gfd/lb/in^2)	4.9 (0.20)	5.9 (0.24)	4.2 (0.17)
Membrane surface area, m^2 (ft^2)	39.5 (430)	35.0 (380)	37.1 (400)
Maximum applied pressure, bars (lb/in^2)	42 (600)	42 (600)	42 (600)
Feed/brine spacer, mm (mil)	0.71 (28)	0.71 (28)	0.71 (28)

Table 14.3 Examples of High-Rejection BWRO Membrane Elements Parameter Commercial Membrane

14.4.3 Brackish Water Desalination Elements

- Low-Fouling BWRO Membrane Elements
  - Low-fouling features of membrane elements **are either obtained by changes of membrane surface chemistry (charge) or by the use of wider feed/brine spacers** [31 or 34 mil (0.79 or 0.86 mm) versus standard 28 mil (0.71 mm)].

- High-Productivity BWRO Membranes
  - Increased productivity of membrane elements is typically achieved **by increasing their total surface area which, in turn, is accomplished by incorporating one additional membrane leaf.**

14.4.4 Seawater Desalination Elements

- Similar to BWRO membrane elements, SWRO membranes can also be classified in four main groups based on their performance:

1. high-rejection,
2. low-energy,
3. low-fouling,
4. high-productivity.

- Standard-rejection membrane elements are designed to remove up to 99.6 percent of the salts in the source seawater.

14.4.4 Seawater Desalination Elements

❑ High-Rejection SWRO Membranes

- High-rejection membrane elements are designed with **tighter membrane structure, which allows to increase the mass of rejected ions and to reject smaller size ions, such as boron**, for example.

❑ Low-Energy (High-Productivity) SWRO Membranes

- Low-energy (high-productivity) SWRO membrane elements are designed with features to operate **at lower feed pressure or yield more product water per membrane element, namely: higher permeability and higher surface area. Increasing the total active membrane leaf**.

14.4.4 Seawater Desalination Elements

❑ Low-Fouling SWRO Membranes

- The low-fouling [also referenced as "**fouling-resistant**" or "low-differential pressure (LD)" feature of most commercially available SWRO membranes at present is obtained by incorporating a wider (typically 34 mil/0.86 mm) **feed/brine spacer in the membrane element configuration at the expense of reducing the number of membrane leafs in the elements**.

Parameter	Commercial Membrane Element Model ESPA 4-MAX Hydranautics	BW30 LE-440 Dow Filmtec	TM720D-440 Toray
Product water flow rate, m^3/day (gpd)	50.0 (13,200)	48.1 (12,700)	45.8 (12,100)
Nominal NaCl rejection, %	99.2	99.3	99.8
Test Feed Pressure, bars (lb/in^2)	10.3 (150)	10.3 (150)	15.8 (225)
Specific flux, Lmh/bar ($gfd/lb/in^2$)	7.7 (0.30)	7.8 (0.31)	7.0 (0.27)
Membrane surface area, m^2 (ft^2)	40.8 (440)	40.8 (440)	40.8 (440)
Maximum applied pressure, bars (lb/in^2)	42 (600)	42 (600)	42 (600)
Feed/brine spacer, mm (mil)	0.71 (28)	0.71 (28)	0.71 (28)

Table 14.6 Examples of High-Productivity BWRO Membrane Elements

14.5 Pressure Vessels

14.5.1 Description

- As shown in Fig. 14.11, RO membrane elements are installed inside pressure vessels (housings) in a series of six to eight membranes per vessel.

- **Typically, one pressure vessel houses six to eight RO membrane elements.**

- A recent design trend in SWRO plants is to install eight elements per vessel.

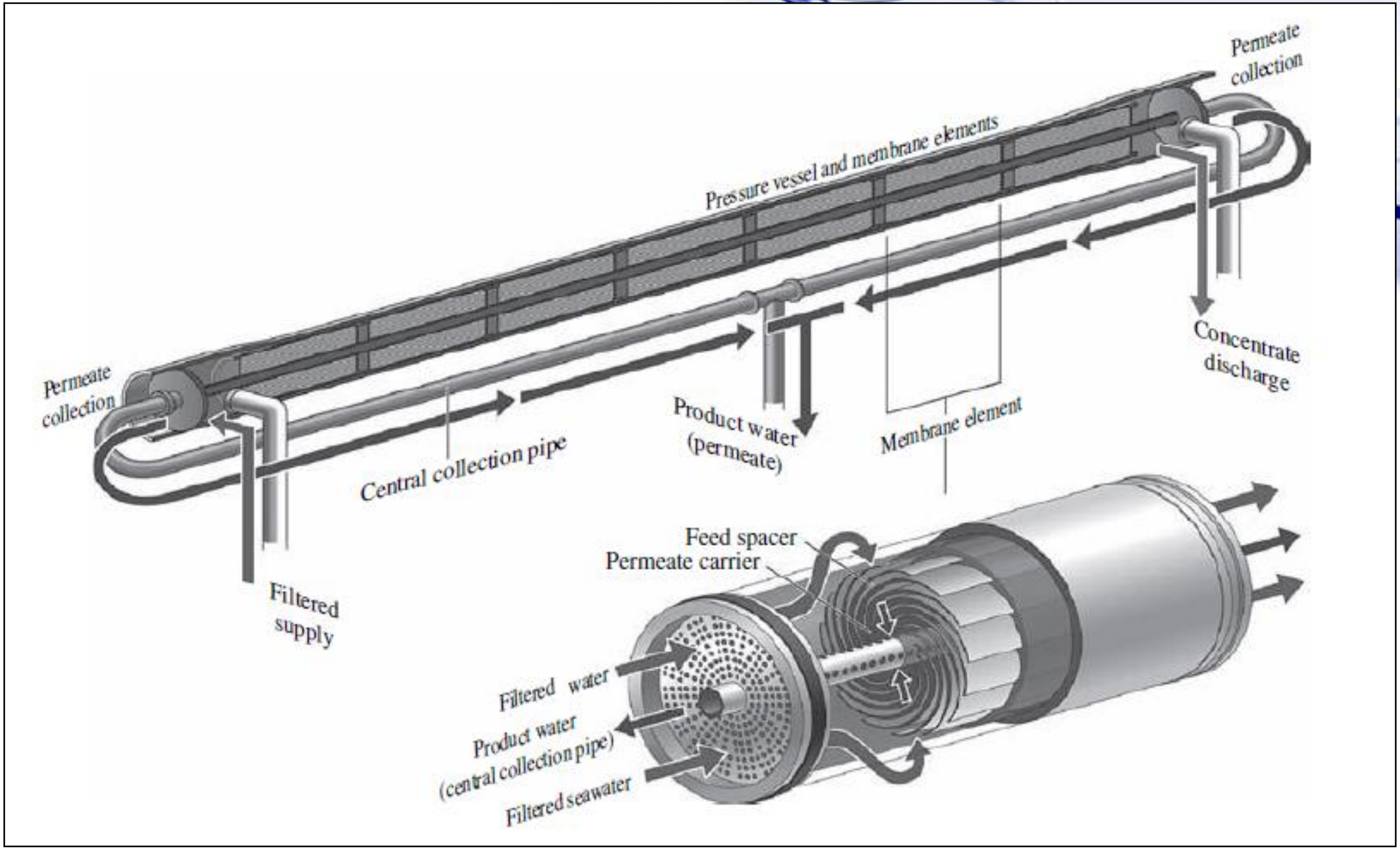

Figure 14.11 Spiralwound- RO membrane elements in vessels.

14.5.1 Description

- **The higher number of membrane elements in the vessel, the higher the differential pressure within the vessels**, and the closest the vessels would operate to the maximum limit of pressure drop (also referred to as differential pressure).

- Recommended by the membrane manufacturers of 4 bars (58 lb/in2) beyond which permanent damage and compaction of the elements may occur.

- In addition, **the use of eight elements will result in a slightly higher feed pressure**.

14.5.1 Description

- The entire volume of feed water to be processed by a given RO vessel is introduced into the front end of the vessel and **applied onto the first membrane element**.
- In most standard pressure-vessel configurations, **permeate and concentrate are collected from the last element**.
- However, as shown in Fig. 14.9, most-recent SWRO system **designs incorporate permeate collection from both the front and back end of the membrane vessels**.
- Previous studies indicate that the use of multiple-port vessels could yield piping cost savings of nearly 50 percent as compared with end-port connection configuration (Sachaf and Haarburger, 2008).

Figure 14.12 Multiple-port pressure vessels.

14.5.3 Alternative Membrane Configurations within the Vessels

- Standard Configuration

- In standard membrane configuration, all membrane elements within the same vessel are identical, and **their flux (fresh water productivity) decreases in the direction of the flow** (see Figs. 3.18 and 14.11).

- As explained previously, this configuration results in **the first two elements producing over 35 to 40 percent of the total plant flow**, expanding feed energy pressure too fast and hindering the performance of the remaining downstream elements.

14.5.3 Alternative Membrane Configurations within the Vessels

- With a typical configuration of seven elements per vessel and ideal uniform flow distribution to all RO elements,
- Each membrane element would produce **one-seventh (14.3 percent) of the total permeate flow of the vessel.**
- However, in actual conventional RO systems, **the flow distribution in a vessel is uneven, and the first membrane element usually produces over 25 percent of the total vessel permeate flow, while the last element only yields 6 to 8 percent of the total vessel permeate**.

14.5.3 Alternative Membrane Configurations within the Vessels

❑ Internally Staged Configuration with Different Membranes

- In the example shown in Fig. 14.13, the first (lead) element in ISD configuration, which receives the entire seawater feed flow of the vessel, is a low-permeability/high salt rejection element (i.e., Dow Filmtec SW30 XHR-400i).
- **Because of its low permeability, this element produces only 14 to 18 percent (instead of 25 percent) of the permeate flow produced by the entire vessel, thereby preserving the feed energy for more effective separation by the downstream RO membrane elements in the vess**el.

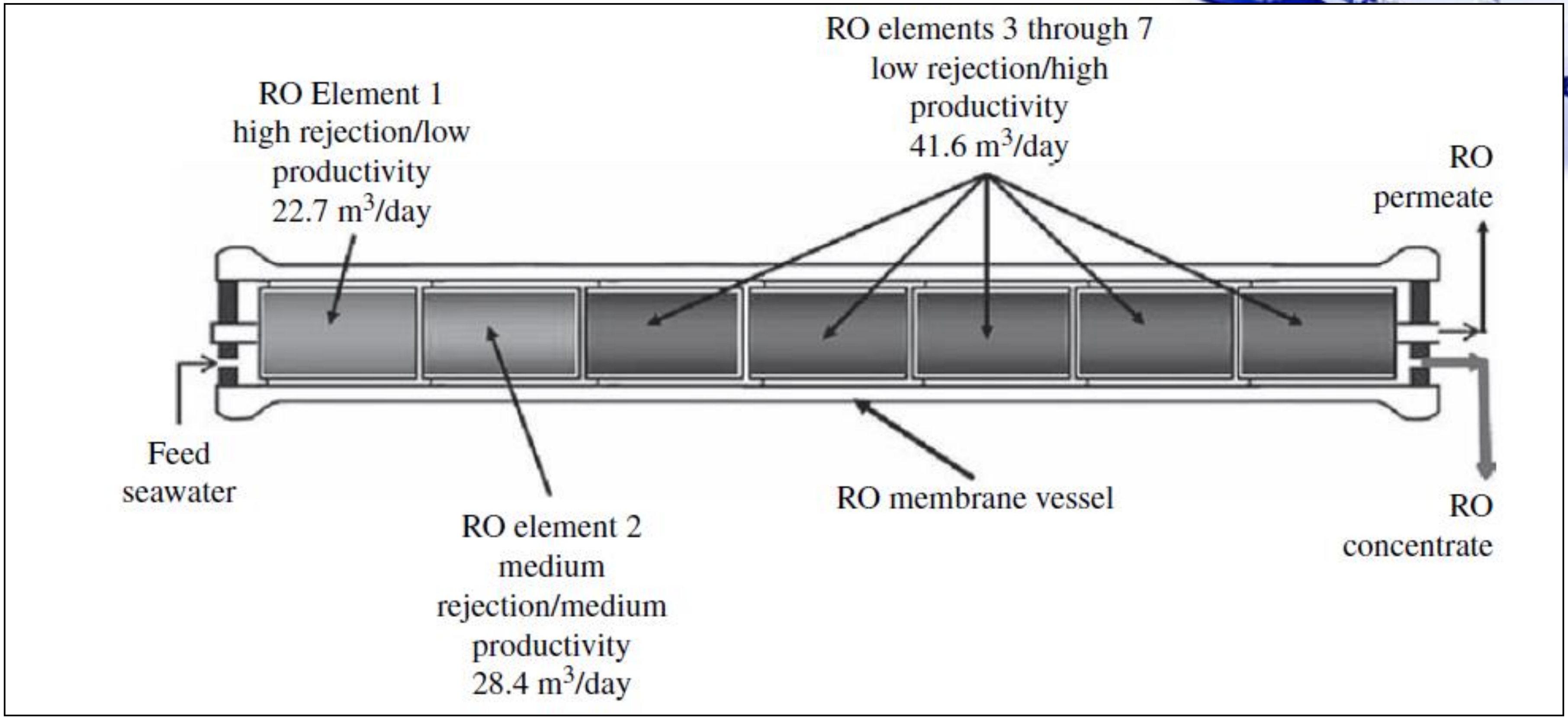

Figure 14.13 Interstage SWRO membrane configuration.

14.6 RO System Piping

- **High-quality stainless steel is typically used for high-pressure feed and concentrate piping of NF and RO systems**.
- The higher the source water salinity and brine concentration, the higher the quality stainless steel is required to prevent the RO system piping from corrosion and to maintain its longevity.

Steel–Common Reference Name	Areas of Application	PREN Number	Notes
316 L and LDX 2101–stainless steel	Permeate, low-salinity brackish water, second-pass RO	25	Not suitable for source seawater of seawater concentrate
2205–Duplex stainless steel	Permeate, high-salinity brackish water, second-pass RO	35	Can be used for source seawater with low DO level and temp. < 14°C
904 L–Duplex stainless steel	Permeate, high-salinity brackish water, second-pass RO	36	Can be used for source seawater with low DO level and temp. < 20°C
254 SMO	All applications	43	Super Austenitic stainless steel
SAF2507 & Zeron 100	All applications	42	Super duplex stainless steel
AL-6XN	All applications	47	Super duplex stainless steel

Table 14.11 Recommended Quality of Steel Piping and Equipment in Contact with Source Brackish Water, Seawater, and Concentrate

14.7 RO Skids and Trains

- Multiple pressure vessels **are arranged on support structures (referred to as skids or racks**).

- The skids are typically made of powder-coated structural steel, plastic-coated steel, or plastic.

- The combination of RO feed pump, pressure vessels, feed, concentrate and permeate piping, valves, couplings, and other fittings (energy-recovery system and instrumentation and controls) installed on a separate support structure (skid/rack), which can function independently, **is referred to as RO train**.

- Each RO train is typically designed to produce **between 10 and 20 percent of the total amount of the membrane desalination product water flow.**

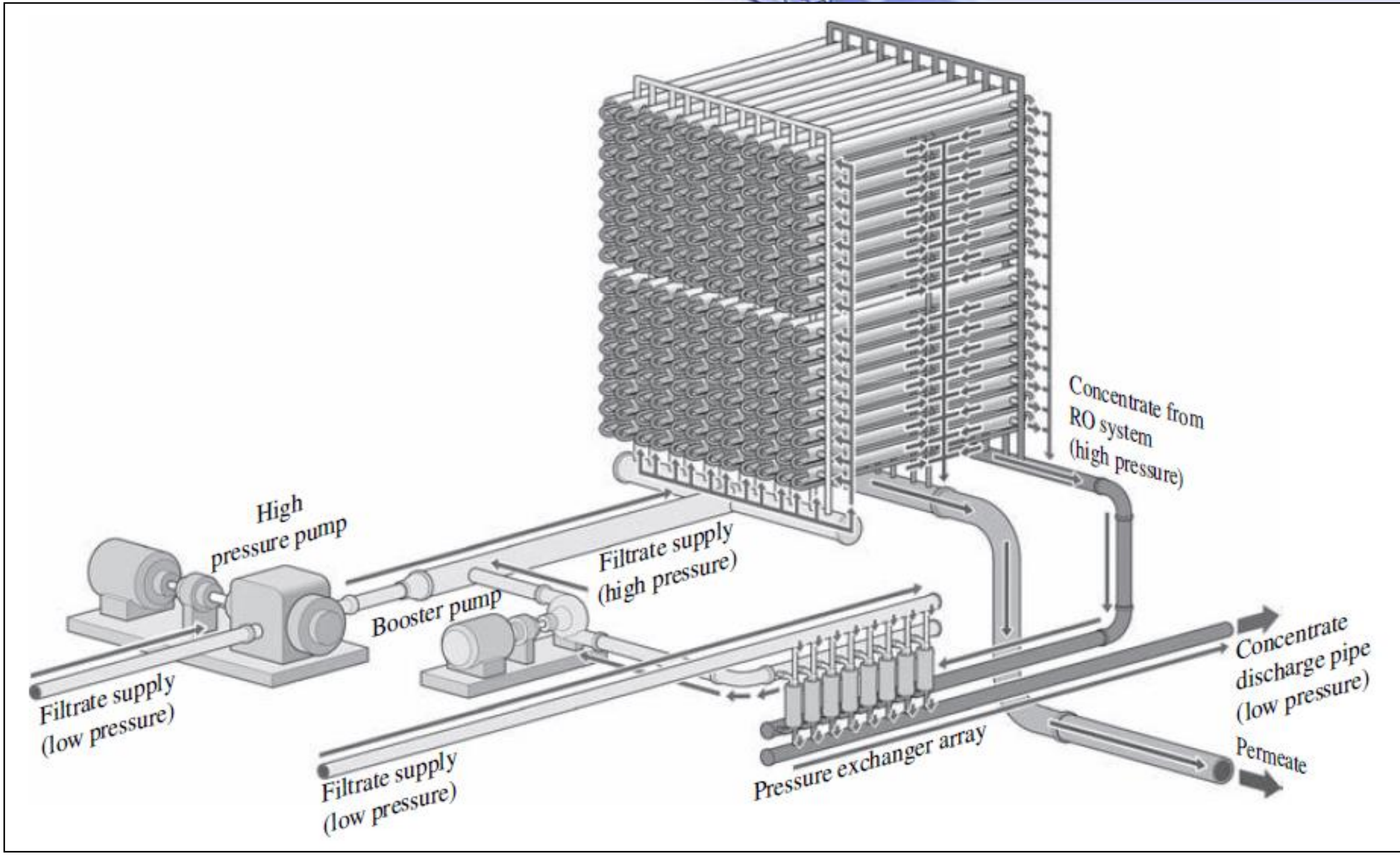

Figure 14.15 SWRO train with an isobaric energy-recovery system.

14.8 Energy Recovery Systems

- A large portion (40 to 50 percent) of the energy applied for desalination of seawater is contained in the concentrate produced by the RO system.

$$ER_{max} = [(F_p - P_d) \times (1 - R)] / F_p$$

- Where,
- ER_{max} is maximum energy that can be recovered from concentrate expressed as percentage of the energy entering the RO system with the feed flow (%).
- F_p is the applied RO feed pressure (bars).
- P_d is the pressure drop across the membranes (bars).
- R is the RO system recovery (%).

14.8 Energy Recovery Systems

❑ Example

- For a SWRO system operating at **feed pressure of 65.0 bars** (925 lb/in2), **43 percent recovery**, and **differential pressure of 1.5 bars** (21.3 lb/in2),

- The maximum energy that can be recovered from the concentrate is **[(65 bars – 1.5 bars) × (1 – 0.43)]/65 bars = 56 percent**.

- This means that if the energy recovery equipment has 100 percent efficiency, it could recover 56 percent of the energy introduced into the RO system.

14.11 RO System Types and Configurations

- depending on the number of sequential RO systems for treatment of permeate and concentrate, RO system configurations could be divided into two main categories:

  1. single- and multipass RO systems.
  2. single- and multistage RO systems.

14.11 RO System Types and Configurations

Single and Multipass RO Systems

- Figure 14.28 shows general schematics of single-, two-, and three-pass RO systems.
- Since each RO **pass provides additional treatment of permeate produced by the previous RO pass, the overall system permeate water quality improves with each pass**.
- Therefore, multipass RO systems are applied when source water salinity is relatively high and the target product water quality cannot be achieved by treating the saline source water by reverse osmosis only once.

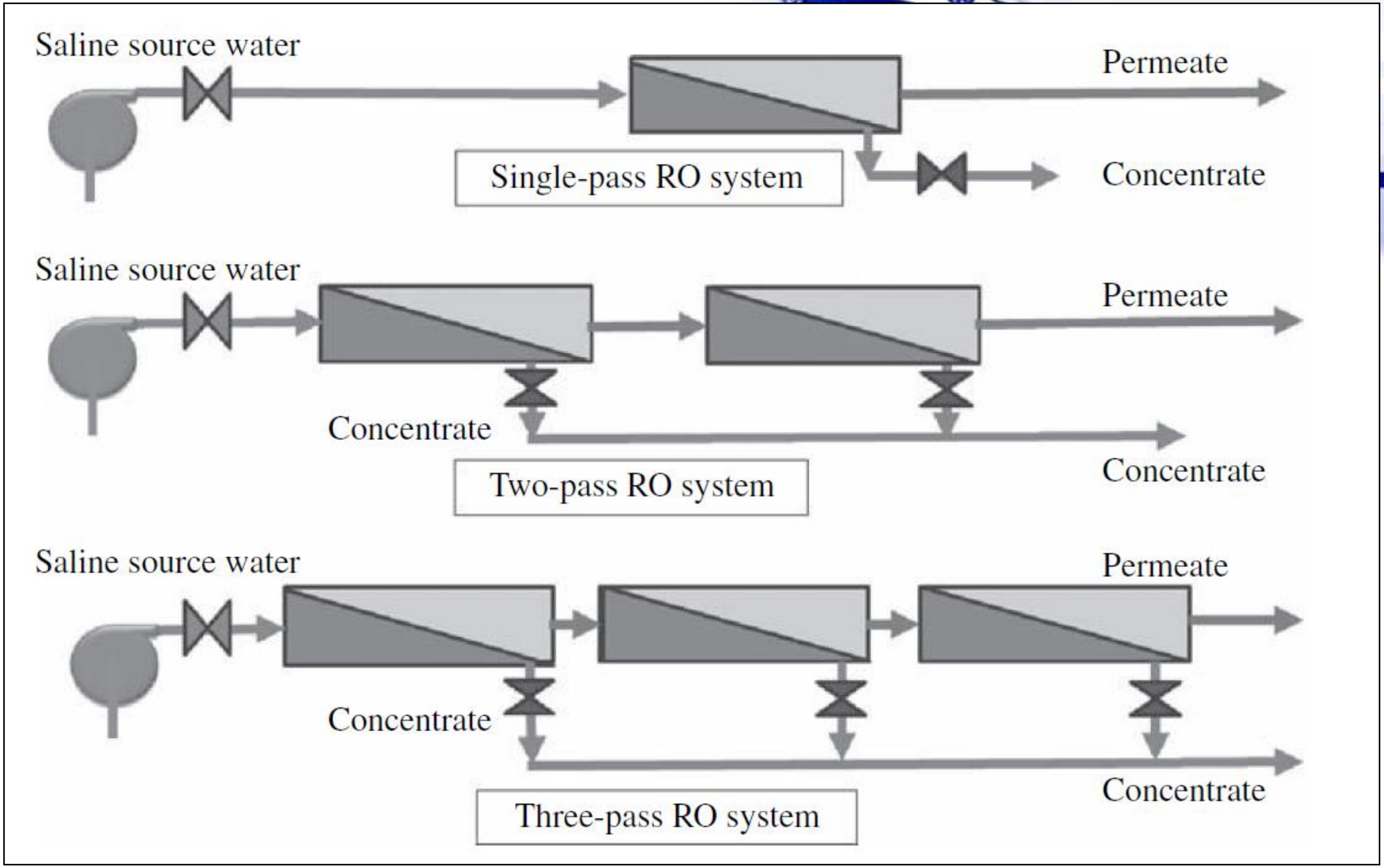

Figure 14.28 Single and multipass RO systems.

14.11 RO System Types and Configurations

❑ Single and Multiple RO Stage Systems

- **In order to reduce the total volume of concentrate (i.e., increase the overall recovery/ produce more fresh water) from the same volume of source water, the concentrate generated by the individual RO passes can be treated by a separate RO system, referenced as "stage."**

- Figure 14.29 depicts single-, two-, and three-stage RO systems.

- Use of multiple stages allows improvement of the overall recovery of the entire RO system.

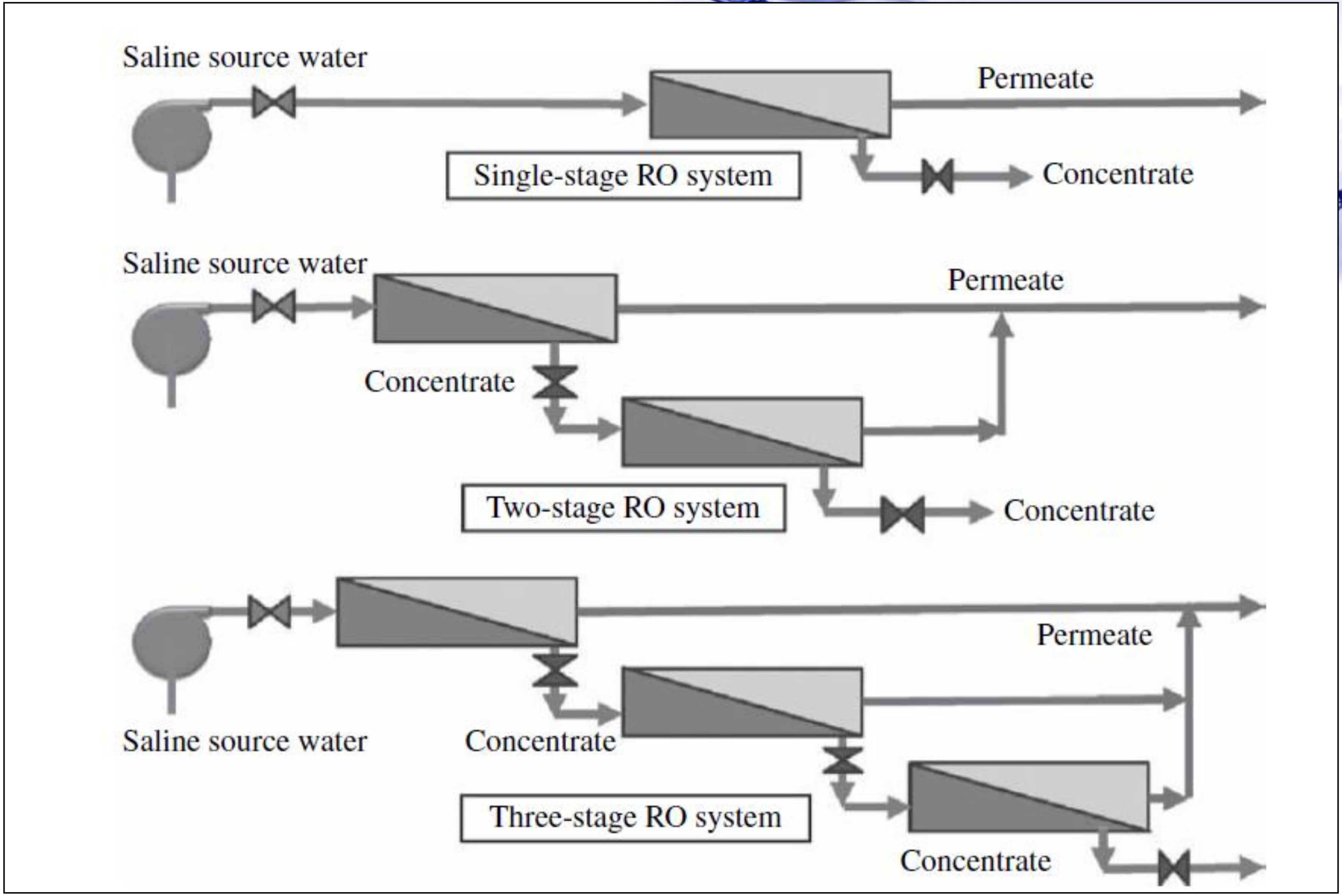

Figure 14.29 Single and multistage RO systems.

14.11 RO System Types and Configurations

- The additional concentrate treatment steps also increase RO system costs.
- The optimum number of stages and passes for a given RO system depends on many factors—such as
  - **source water quality.**
  - **target permeate water quality and fresh water production flow.**
  - **cost of equipment and energy.**
  - **and should be determined based on the site specific conditions of each project.**

14.11 RO System Types and Configurations

❑ Seawater System Configurations

- The SWRO system configurations **most widely applied at present include single-pass treatment**, where the source water is processed by RO only once (Fig. 14.33), and two-pass RO treatment, where the seawater is first processed through a SWRO system, and then permeate produced by this system is reprocessed by brackish RO membranes (see Figs. 14.34 and 14.35).

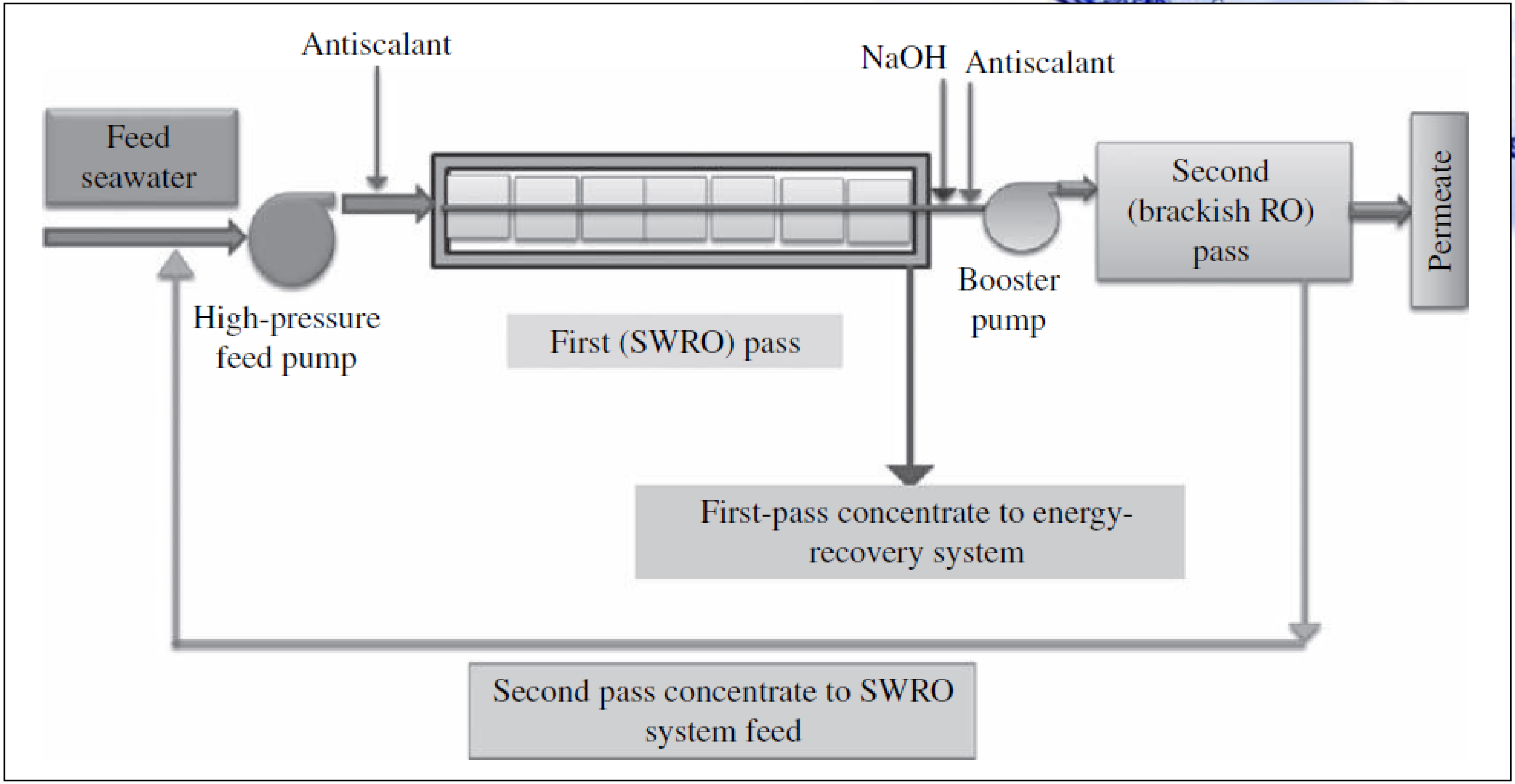

Figure 14.34 Conventional full two-pass SWRO system.

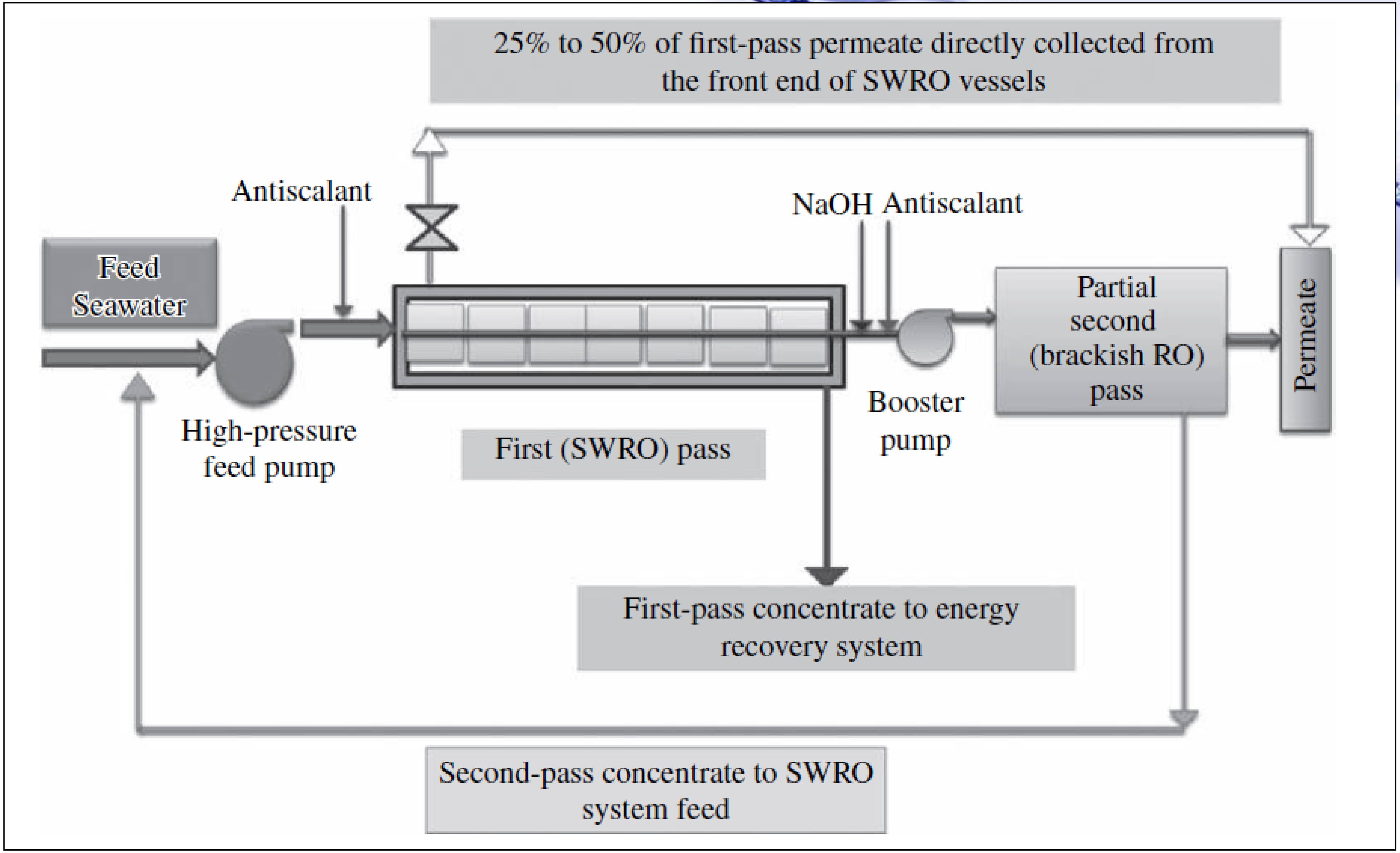

Figure 14.35 Split-partial two-pass SWRO system.

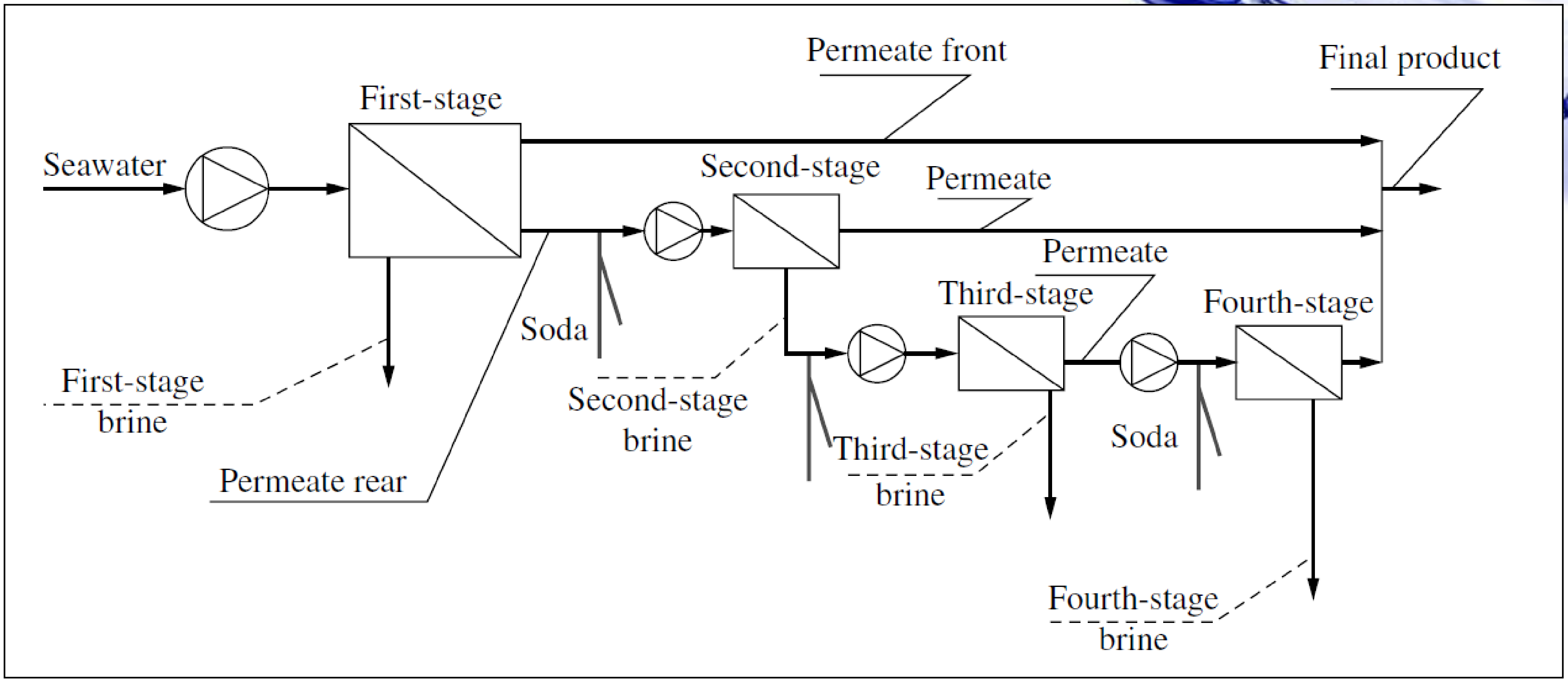

Figure 14.36 Ashkelon four-stage SWRO system (Gorenflo et al., 2007).

14.12 Planning and Design Considerations

- 14.12.1 **General Design Methodology**

- Key steps associated with the design of RO desalination system include:

  1. **Source water quality characterization.**
  2. **Determination of target product water quality, quantity and operations regime.**
  3. **Selection of RO system configuration.**
  4. **Selection of key RO system-performance parameters.**

14.12.1 General Design Methodology

❖ Step 1. Source Water Quality Characterization

- The first step of the RO system design is to establish the water quality that will be introduced into the RO membranes.

- Besides determining the raw source water quality, the project designer will also need **to determine how this water quality will be changed by the plant pretreatment processes in terms of content of salts, foulants, oxidants, and temperature**.

❖ Step 2. Determination of Target Product Water Quality, Quantity, and Plant Operations Regime

- The next step in the design process **is to determine the product water quality specifications of the desalination plant and its target annual production capacity, installed capacity, and availability factor**.

14.12.1 General Design Methodology

- **Example:**

- For a plant with an annual design production capacity of 40,000 m3/day (10.6 mgd).
- a design availability factor of 96 percent means that 96 percent of the time (i.e., 350 out of 365 days) the desalination plant will have to be designed to produce 40,000 m3/day (10.6 mgd) or more.
- Most desalination plants are designed with a target availability factor of 90 to 95 percent.
- The higher the design availability factor, **the more conservative the RO system design should be, and the higher the design safety factor/installed redundant production capacity.**

14.12.1 General Design Methodology

❖ Step 3. Selection of RO System Configuration and Membrane Element Type

- The BWRO system will be selected if the source water salinity is between 500 and 10,000 mg/L.

- As indicated previously within this salinity range, the BWRO system could be designed as **a low-salinity BWRO system with a 5 to 50 percent source water bypass if the feed water salinity is below 2000 to 2500 mg/L**,

- Depending on the actual product water and source water quality and target overall system recovery, **the BWRO system could be configured as a single-stage or two-stage RO system.**

14.12.1 General Design Methodology

- A general rule of thumb is that for **six, seven, and eight elements** per vessel in BWRO systems, the maximum recovery that could be achieved per stage is **55, 65, and 75 percent**, respectively.

- Selection of the number of plant RO trains is mainly driven by the plant design capacity **turndown ratio and the target plant capacity availability factor**.

- For example, if a given RO plant will need to be designed for a minimum turndown capacity ratio of 10 percent, this requirement would necessitate the size of the individual RO trains to be designed to produce 10 percent of the total plant permeate flow, so if the plant production capacity is turned down to 10 percent, then only RO train will be kept in operation.

14.12.1 General Design Methodology

- In this case, a 40,000 m3/day (10.6 mgd) plant would be designed with 10 RO trains, each with production capacity of 4000 m3/day (1.1 mgd)—i.e., 10 percent of the flow.
- If the plant has **relatively low target availability factor—say, 90 percent**—then the plant train is usually oversized with only 8 to 10 percent, especially if each RO train produces only 10 percent of the total flow—i.e.,
- **the individual RO trains will be sized for target installed capacity of 1.1 × 4000 m3/day = 4400 m3/day (1.16 mgd).**

14.12.1 General Design Methodology

❖ **Step 4. Selection of Key RO System Performance Parameters**

- **RO system performance projection computer software available from major RO membrane manufacturers could be used in order to project and optimize the type and number of RO system membrane elements per vessel and vessels per train, as well as key RO feed pump design criteria and permeate and concentrate water quality**.
- Such RO performance projection software can be downloaded from a membrane supplier’s website.

14.12.1 General Design Methodology

- Popular software packages commonly used for this purpose are IMSDesign from Hydranautics, **ROSA from Dow Filtmtec**, TorayDS from Toray Membranes, and ROPRO from Koch Membrane Systems.

- During the design process, the membrane supplier software could be used iteratively to analyze the feasibility of various RO system configurations and membrane elements.

14.12.2 Design Example: BWRO System

- The source water is anaerobic and contains total sulfide concentration of 5 mg/L.
- **The target product water quality TDS concentration is 250 mg/L.**
- The BWRO plant will need to produce finished water suitable for potable use.
- Since the source water salinity is relatively high and is made up mainly of sodium and chlorides, this water will need to be treated with BWRO membrane system.

14.12.2 Design Example: BWRO System

- **This system will be designed to treat the entire source water flow without bypass**.

- Because of the high cost of the only available concentrate discharge alternatives —deep injection wells— the system would be designed for relatively high recovery of 75 to 80 percent.

- Achieving such recovery will necessitate the use of a two-stage BWRO system.

Component/Parameter	Specifications/Design Criteria
• Feed water • Design flow rate, m^3/day (mgd) • TDS • Temperature	51,000 m^3/day (13.5 mgd) 3600 mg/L 20 to 25°C (68 to 77°F)
RO membranes	
Unit product water capacity	9500 m^3/day (2.5 mgd)
Number of RO skids	4
Number of stages	2
Number of pressure vessels in first & second stage	40/20
Number of RO elements per vessel	7
Total number of RO elements	420
RO membrane element size	8 × 40 in
Type of BWRO elements	Standard BWRO spiral wound
Design system recovery	75%
Average membrane flux	25.5 Lmh/15 gfd

Energy Recovery Device	
Type	Turbocharger
Number of units	4 (One per RO Skid)
First-stage concentrate flow	295 m^3/h (1300 gpm)
Second-stage concentrate flow	170 m^3/h (750 gpm)
Second-stage concentrate pressure	21 bars (300 lb/in^2)
Concentrate system back pressure	1.8 bars (25 lb/in^2)
Interstage booster pressure	4.6 bars (65 lb/in^2)
RO system energy use, kWh/m^3 (kWh/1000 gal)	1.2 kWh/m^3 (4.5 kWh/1000 gal)
Materials of construction	
Frame	Epoxy-coated aluminum
Pressure vessels	FRP
Feed water piping	Duplex stainless steel
Concentrate piping	Duplex stainless steel–high pressure/ PVC schedule 80, low pressure
Permeate piping	PVC schedule 80
Energy recovery devices	Duplex stainless steel

Table 14.21 Example of Key Design Criteria for 40,000 m3/day (10.6 mgd) BWRO Desalination System

14.12.3 Design Example: SWRO System

- The SWRO plant is designed to **produce drinking water.**
- Because of the high salinity and temperature of the source seawater and the relatively low target product water **TDS, boron and bromide concentration of 250 mg/L, 0.75 mg and 0.5 mg/L, respectively**,
- the SWRO system will be designed with **two passes—first-pass SWRO and second-pass BWRO with two stages**.
- The second pass will have two stages in 2:1 array.
- The total plant recovery is **40.5 percent**.

14.12.3 Design Example: SWRO System

- Assuming that the plant has to be designed for very high level of availability (i.e., **96 percent or more**),
- the actual installed plant capacity is selected to be **15 percent higher than the average annual production capacity**—i.e.,
- the installed RO system capacity is

1.15 × 40,000 m3/day = 46,000 m3/day (12.15 mgd).

Component/Parameter	Specifications/Design Criteria
Feed Water • Design flow rate, m^3/day (mgd) • TDS • Temperature	119,100 m^3/day (31.5 mgd) 42,000 mg/L 15 to 38°C (59 to 100°F)
RO membrane skids	
Unit product water capacity	9200 m^3/day (2.43 mgd)
Number of RO skids	5
Number of passes	2 (first-pass SWRO and full second-pass BWRO)
First (SWRO) pass	
Number of stages	1
First-pass recovery rate	43%
Number of pressure vessels per skid	107
Number of RO elements per vessel	7
Total number of SWRO elements	749
RO membrane element size	8 × 40 in
Type of SWRO Elements	SWC4B max (see Table 14.8)
Flow produced by the first pass	10,240 m^3/day (2.7 mgd)
Average membrane flux	14 Lmh/8.2 gfd

High-pressure RO feed pump	
• Number of pumps	5 (one per RO skid)
• Unit pump capacity	430 m^3/h (1900 gpm)
• Operating feed pressure	60.4 bars (875.8 lb/in^2)
• Maximum delivery pressure	75 bars (1087 lb/in^2)
• Pump efficiency	85%
Second (BWRO) pass	
Number of stages	2
Second-pass recovery rate	90%
Number of pressure vessels in stage 1	26
Number of pressure vessels in stage 2	13
Number of RO elements per vessel	7
Total number of BWRO elements per skid	273
RO membrane element size	8 × 40 in
Type of SWRO Elements	ESPAB max

Table 14.22 Example of Key Design Criteria for 40,000 m3/day (10.6 mgd) SWRO Desalination System

Component/Parameter	Specifications/Design Criteria
Flow produced by the second pass	9200 m^3/day (2.43 mgd)
Average membrane flux	34.4 Lmh/20.2 gfd
Second-pass feed pump • Number of pumps • Unit pump capacity • Operating feed pressure • Maximum delivery pressure • Pump efficiency	5 (one per RO skid) 430 m^3/h (1900 gpm) 18 bars (261 lb/in^2) 22 bars (319 lb/in^2) 82%
Energy recovery device	
Type	Pressure exchanger: ERI PX 260
Number of pressure exchangers per RO train	12
Concentrate/permeate flow per 12 PX units	640 m^3/h (2800 gpm) 53.3 m^3/h (560 gpm)/PX unit
RO feed pressure	60.4 bars (875.8 lb/in^2)
Energy-recovery efficiency	95%
RO system energy use, kWh/m^3 (kWh/1000 gal)	3.0 kWh/m^3 (11.3 kWh/1000 gal)
Materials of construction	
Frame	Epoxy-coated steel
Pressure vessels	FRP
Feed water piping	Super duplex stainless steel
Concentrate piping	Super duplex stainless steel–high pressure/ PVC schedule 80–low pressure
Permeate piping	PVC schedule 80
Energy recovery devices	Super duplex stainless steel

Table 14.22 Example of Key Design Criteria for 40,000 m3/day (10.6 mgd) SWRO Desalination System (Continued)

Design Exercise using:

ROSA from Dow Filtmtec

14.13 RO System Desalination Costs

- The construction costs of some of the key membrane SWRO system elements are summarized in Table 14.23.
- **Approximately 10 to 20 percent has to be added to those costs shown in Table 14.23 for shipping, handling, installation oversight, and insurance**.
- **The cost of the membrane RO modules (trains) is proportional to the design capacity and flux of the SWRO system. Typically, one RO module contains 50 to 200 membrane vessels**.

Item	Construction Cost ($/Item or as Indicated)
8-in brackish RO membrane elements	$250–$350/element
8-in SWRO membrane elements	$400–$600/element
16-in SWRO membrane elements	$2800–$3300/element
Brackish RO pressure vessels for 8-in elements	$1000–$1300/vessel
SWRO pressure vessels for 8-in elements	$1300–$1800/vessel
SWRO pressure vessels for 16-in elements	$3600–$5000/vessel
RO Train piping	$250,000–$750,000/ RO train
RO Train support frame	$150,000–$550,000/ RO train
RO Train instrumentation and controls	$30,000–$150,000/RO train
High-pressure pumps	$150,000 –$2,400,000/RO train

Note: All costs in year 2012 $US.

Table 14.23 Construction Costs of Key Membrane RO System Components