THE MIDDLE EAST DESALINATION RESEARCH CENTER

Cost Estimating of SWRO Desalination Plants

Day 1: Plant Cost Fundamentals

June 25, 2013

14:45-15:45

1.4 RO System Construction Costs

Water Globe Consulting

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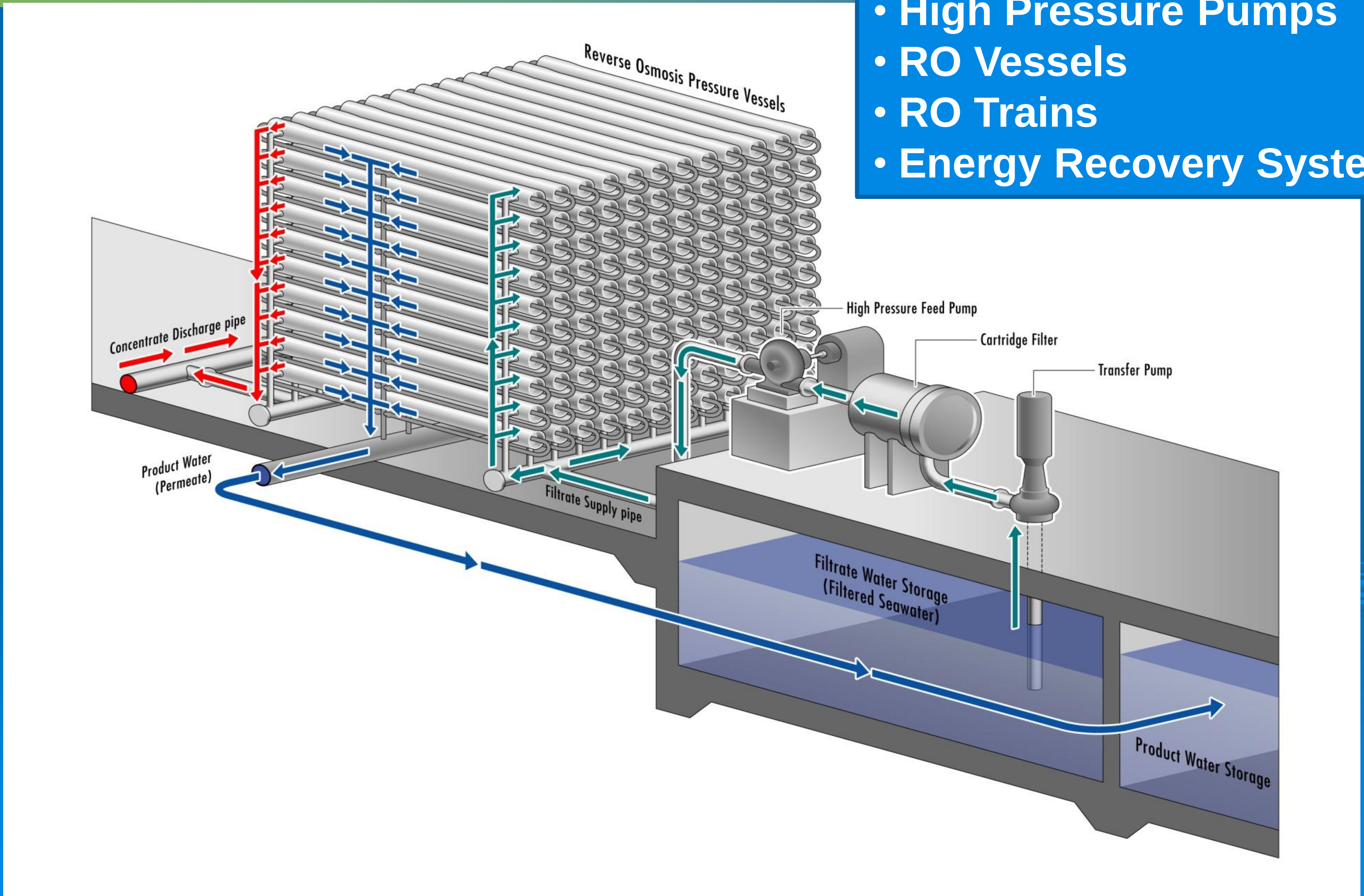
RO System Construction Costs - Outline

- Key SWRO System Components
- High Pressure Pump Costs
- Costs of Membrane Racks
- Energy Recovery System Costs

Key RO System Components

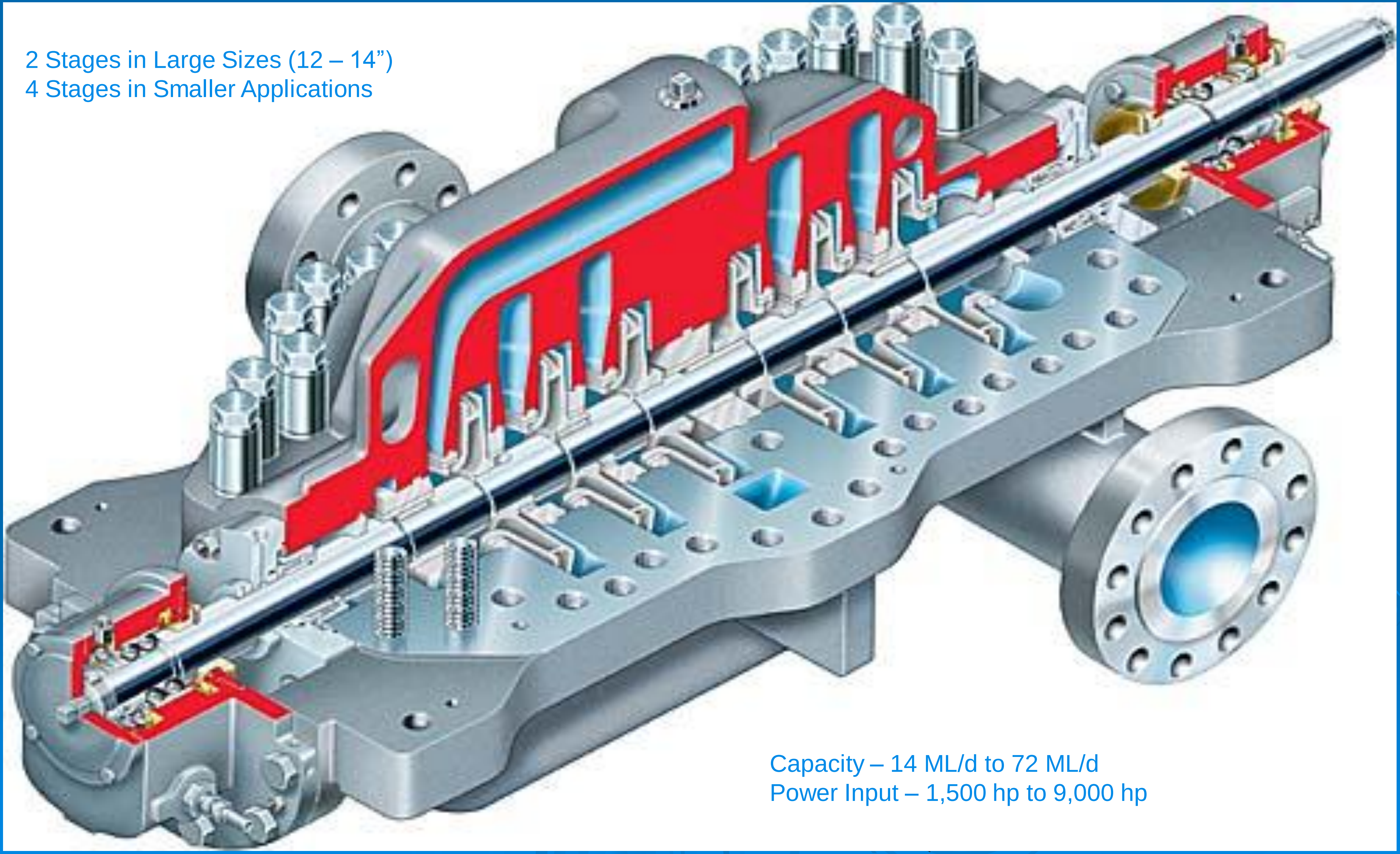
- High Pressure Pumps
- RO Vessels
- RO Trains
- Energy Recovery System



Types of SWRO Feed Pumps

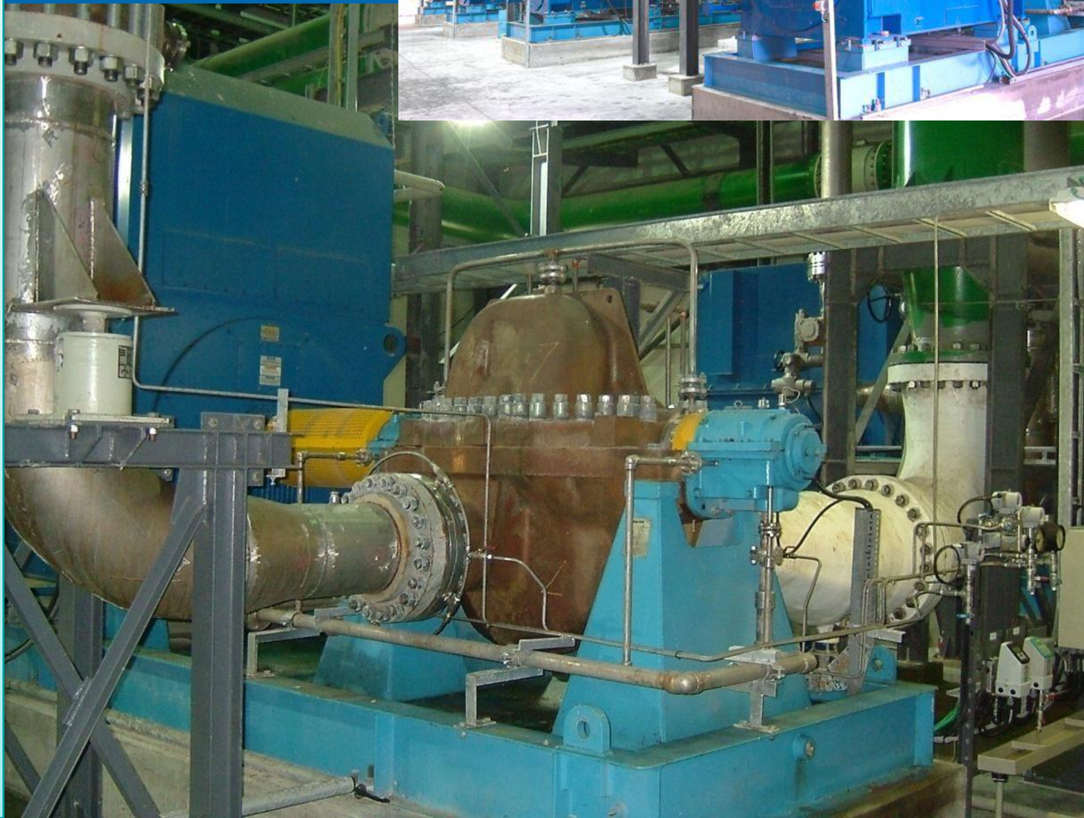
- Reciprocating (Positive Displacement/Piston) Pumps;
  - Applications Typically Limited to 1.0 MGD;
  - 90 % to 95 % Efficiency;
  - Flat Pump Curve – Efficiency and Flow Constant at Changing Membrane Pressures.
- Centrifugal Pumps:
  - Available in All Sizes;
  - 82 to 88 % Efficiency;
  - Pump Efficiency Varies with Changing Membrane Pressure.

Horizontally Split-Case Pumps



Ashkelon - Largest Horizontally-Split High Pressure Pumps In Use Today

- Two Sets of 3+1 Two-stage Horizontal Split-case Pumps – 60 ML/d each
- Pump Motors – 5.2 MW
- 5-year Pump Efficiency Guarantee
- All Wet Parts Made of Duplex Stainless Steel
- Gold Coast – Similar Configuration (3+1/4.8 MW)



Radially Split Case Pumps

- Occupy Less Space;
- Easier to Maintain;
- Less Vibrations;
- Only One Mechanical Seal on the Drive End (Horizontally Split Case Pumps Have2 seals);
- Internal Fiber-Composite Bearings (Water Lubricated) – vs. External Grease Lubricated;
- Largest Pumps First Installed for Expansion of Dhekelia SWRO Plant (Cyprus) to 50 ML/d;
- Unit Capacity – 25 ML/d (2,800 hp) – 87 % Efficiency.

Segmental-Ring Pumps

- Individual Pump Stages Located Between Pump Suction and Discharge Casings.
- Impellers Mounted on Common Shaft.
- Smaller Diameter;
- Lighter Construction;
- Lower Cost.

Maximizing Pump Efficiency – Bigger Pumps Rule!

- Pump Efficiency ~ $n \times (Q/H)^{0.5} \times (1/H)^{0.25}$

Where:

n = pump speed (min^{-1});
Q = nominal pump capacity (m^3/s);
H = pump head (m).

<u>Pump Efficiency</u>:
One Pump Per Train – 83 %;
One Pump Per 2 Trains – 85 %;
Three Pumps Per 16 Trains – 88 %.

Perth –
One Pump per 2 RO Trains

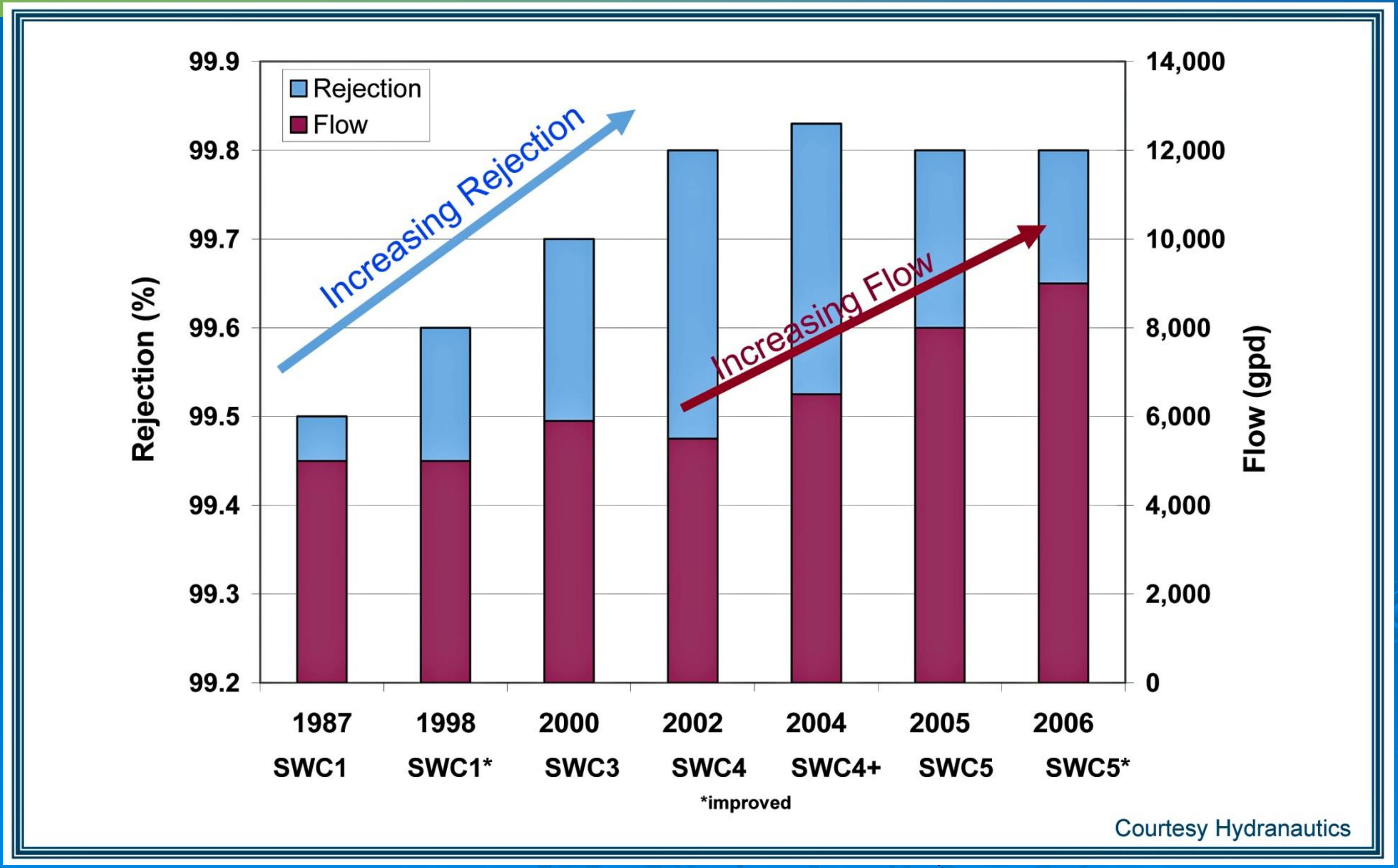
Ashkelon, Israel –
(3+1) 7,100-hp Pumps per 16 RO Trains

RO Trains – Alternative Configurations

Key SWRO System Components

- Membrane Elements:
  - Diameter 4” to 16” (8” – most widely used);
  - Length – 40-in (60-in also available).
- Membrane Vessels:
  - Fiberglass Reinforced Plastic;
  - 6 to 8 Membranes per Vessel;
  - Installed on Welded Steel or FRP Support Racks.
- Membrane Process Trains:
  - Membrane Vessels Connected with Ports to Feed, Concentrate and Product Water Lines.

SWRO Membrane Elements – Technology Evolution



Large SWRO Membrane Elements

16" RO Membrane Element

Large Size RO Membranes – Advantages

- Potential Space Savings – 10 to 15 %.
- Capital Cost Savings – 5 to 10 %.
- Total Cost of Water Savings – 4 to 6 %

Potential Disadvantages

- Loading Requires Special Equipment and Extra Space;
- Special Costlier Vessels & End Caps Needed;
- More Costly Foundations and Structure May Be Needed
- Membranes Costlier to Manufacture.

Standard 8" RO Membrane Element

Large Size SWRO Elements -Productivity

Typical Production Capacity of One Large RO Vessel			
Membrane Manufacturer/ Membrane Element Size	**Typical Number of Elements per Vessel**	**Product Water Capacity per Vessel (MGD)**	
		BWRO & Water Reuse	**SWRO**
Dow/Filmtec 16-in x 40-in	7	0.28-0.30	0.22
Hydranautics 16-in x 40-in	4	0.12-0.15	0.10-0.14
Toray 16-in x 40-in	7	0.28	0.19-0.21
Woongjin Chemical 16-in x 40-in	4	0.15	0.10-0.15
KMS – MegaMagnum 18-in x 61-in	5	0.33-0.43	0.26-0.35
KMS – MegaMagnum Plus – 19-in x 61-in	5	0.40-0.50	0.30-0.40

Note: 1 MGD = 3,785 m^3/day

Projects with Large RO Elements

	Location	Project Name	Capacity (MLD)	Start-Up Date
Koch Membrane Systems	USA, Yuma, Ariz.	Metropolitan Water District of Southern California, BWRO demonstration	1.9	2005
Koch Membrane Systems	Australia	Industrial Maltery, water reuse	1.5	April 2006
Koch Membrane Systems	USA, Goodyear, Ariz.	City of Goodyear, Ariz., BWRO	1.9	May 2007
Koch Membrane Systems	Australia	Bundamba AWT Plant, Stage 1A, water reuse	29.9	Aug. 2007
Koch Membrane Systems	USA, Waupun, Wisc.	City of Waupun, Wisc. (ULP)	7.6	Dec. 2007
Koch Membrane Systems	Australia	Bundamba AWT Plant, Stage 1B, water reuse	36.0	April 2008
Koch Membrane Systems	USA, Moscow, Ohio	Tate–Monroe Water Association, US52 WTP Project, TFCS Softening	7.6	3rd Quarter 2008
Koch Membrane Systems	Ukraine	Alchevsk Steel Mill, wastewater treatment	15.1	4th Quarter 2008
Koch Membrane Systems	Canary Islands	Hotel—SWRO Demonstration	N/A	N/A
Hydranautics	Singapore	PUB: Bedok NEWater, water reuse ESPA BWRO (GrahamTek) pilot	N/A	Aug. 2006
Hydranautics	Singapore	PUB: Bedok NEWater, water reuse ESPA2 BWRO (GrahamTek)	54.9 (~39.4 Phase 1 and ~15.5 Phase 2)	Phase 1: May 2008 Phase 2: Dec. 2008
Hydranautics	UAE, Layyah	SWC3 SWRO Pilot (GrahamTek)	1.0	April 2007
Hydranautics	Canary Islands	SWC5 SWRO Pilot (GrahamTek)	N/A	Oct. 2007
Hydranautics	Singapore, PowerSeraya	SWC3 Seawater RO (GrahamTek)	10.0	Jan. 2008
Hydranautics	Saudi Arabia	SWRO Pilot	N/A	2009
Hydranautics	Spain	SWRO Pilot	N/A	2009
Toray	Singapore	Changi, water reuse (TML40-160) pilot	N/A	N/A
Toray	Malta	Sabha III, SWRO demonstration	N/A	2009
Woongjin Chemical	Singapore	PUB: Bedok NEWater , water reuse (RE16040) (GrahamTek) pilot	1.4	Oct. 2006
Woongjin Chemical	Singapore	PUB: Bedok NEWater, water reuse (RE16040-BLR) (GrahamTek)	29.9	May 2008
Woongjin Chemical	Australia	Yabulu, SWRO	6.0	2009
Dow	Singapore	PUB: Bedok NEWater, water reuse pilot	1.2	Sept. 2007

N/A = Not available
SWRO = Seawater RO
BWRO = Brackish water RO

Courtesy: Bergman & Losier

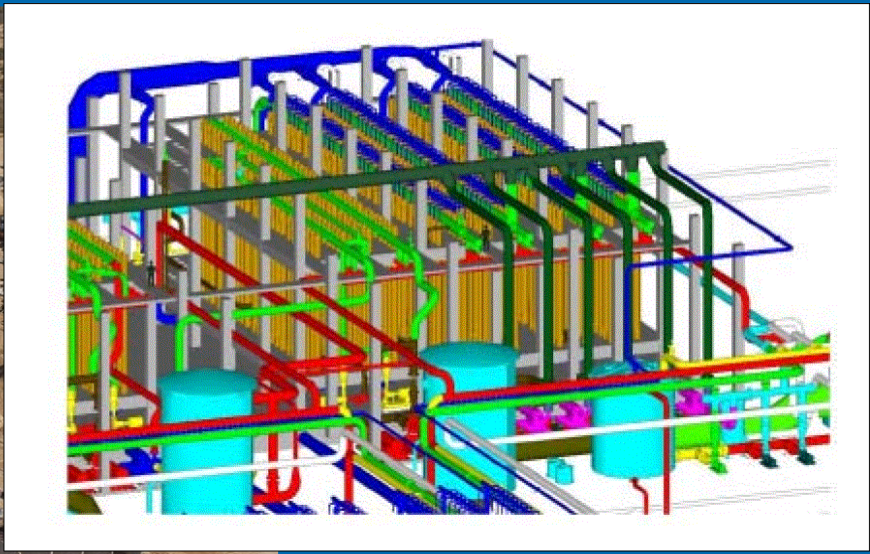
Horizontal vs. Vertical Pressure Vessel Configuration

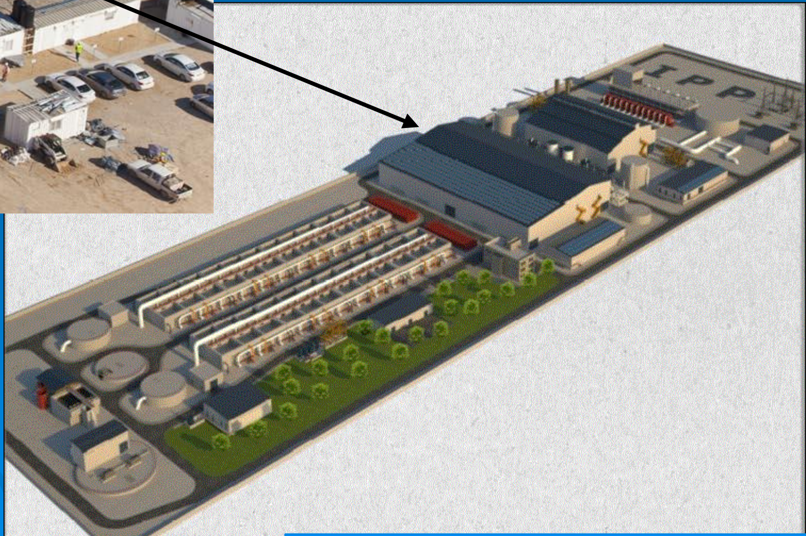
- Horizontal Pressure Vessels Dominate SWRO Plant Configurations with 8-inch Elements:
  - Easier Manual Handling;
  - 1.5 Times Lower Height Buildings;
  - Lower Cost Foundations.

- Vertical Pressure Vessel Configuration – Found More Attractive for 16-inch Elements Where Manual Membrane Handling is Not Possible.
  - 1.5 Times Smaller Footprint;
  - 1.2 Times Less Super Duplex Piping & Fittings;
  - 15 % Lower Plant Construction Costs.

BEL's 16-inch diameter, 8-element Pressure Vessel

410 MLD Sorek SWRO Plant, Israel





- Vertical 16-inch Vessels;
- 4.3 Times Larger Flow Rate than 8-inch Membranes;
- Scheduled for Operation in 2013;
- Record Low Water Price (US¢ 58.5/m³ - in $2009)

Courtesy: IDE Technologies

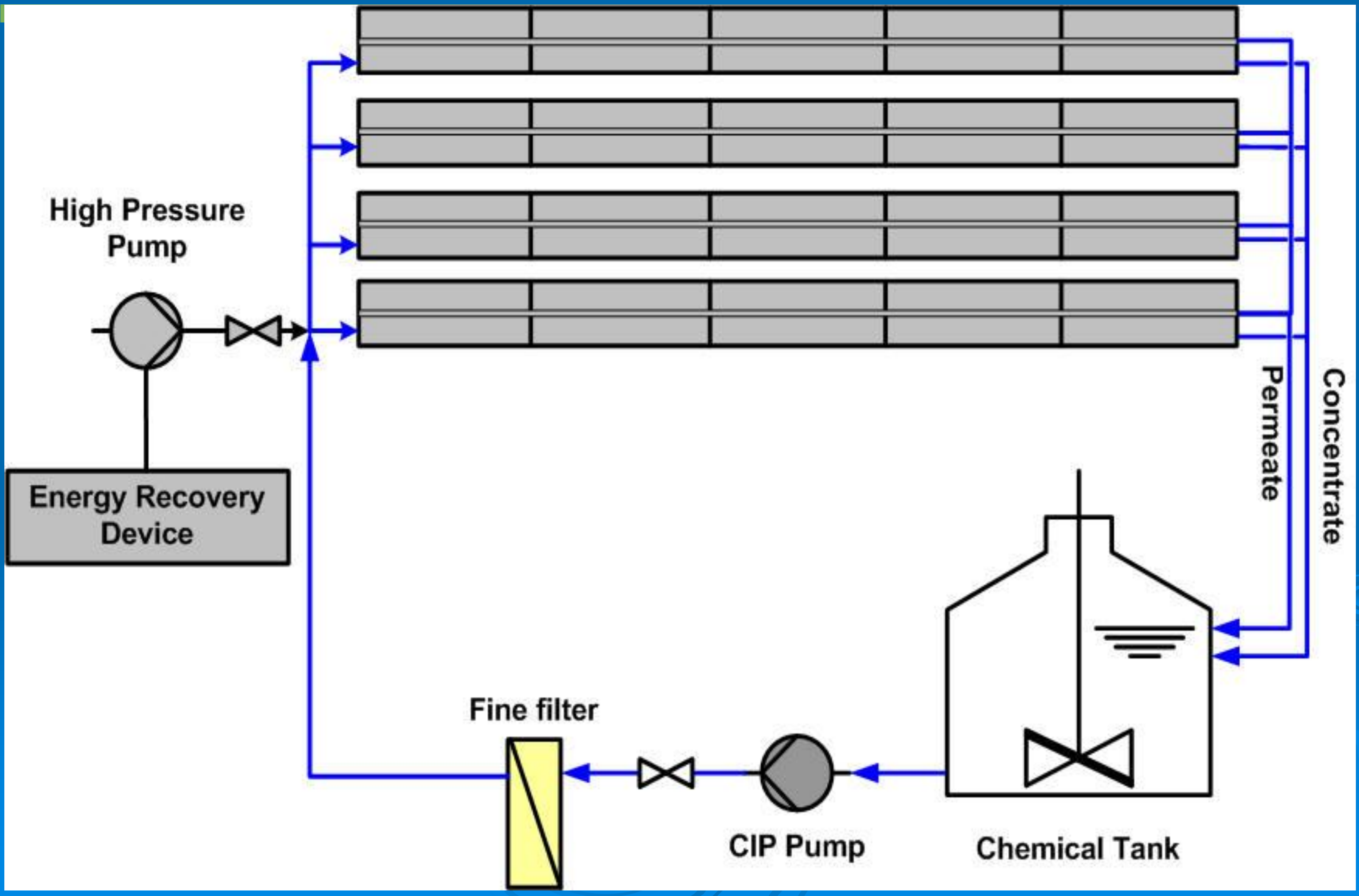
Membrane Vessels

- Key Manufacturers:
  - Pentair (Codeline) – www.codeline.com
  - BEL Composite America, Inc. – www.belvessels.com
  - Bekaert Progressive Composites, Corp. www.bekaert.com

Membrane Vessels – Multiple Ports

Membrane Vessels – Flow Distribution System

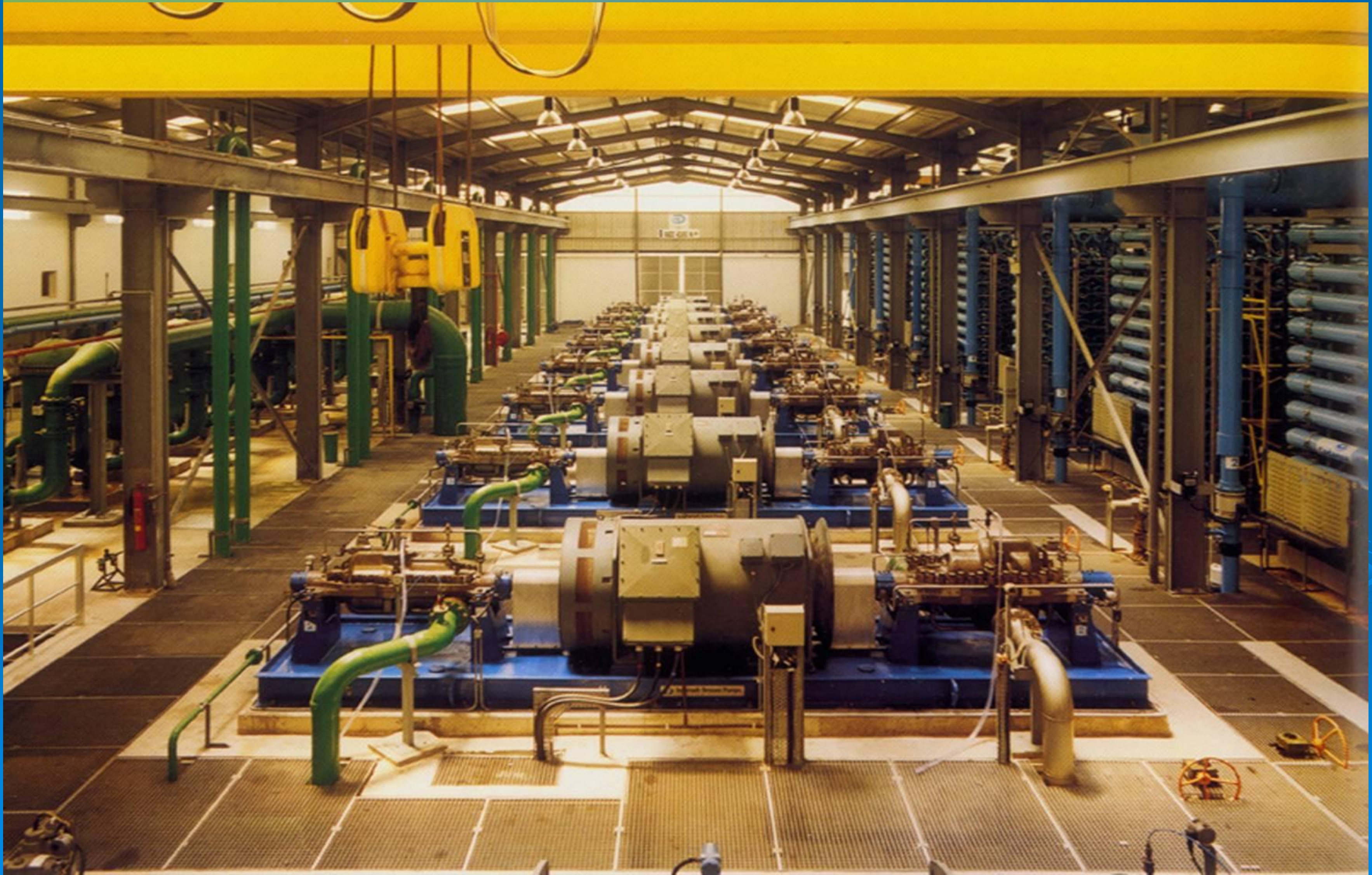
RO Membrane Cleaning System



RO Membrane Trains – Alternatives

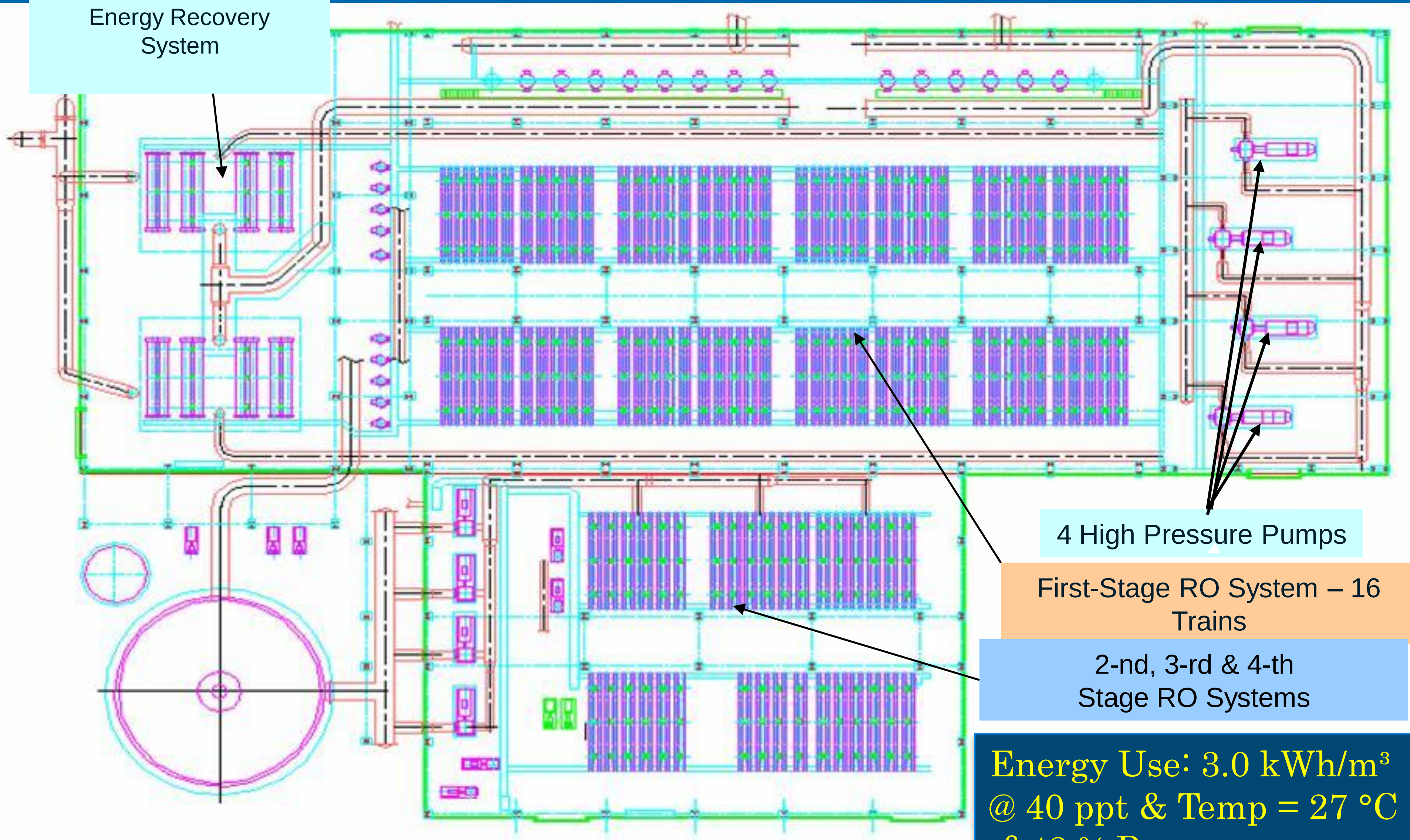
- One High Pressure Pump Per One RO Train
- One High Pressure Pump per Two RO Trains
- One High Pressure Pump Serving 50 % of the Trains

One HP Pump – One RO Train



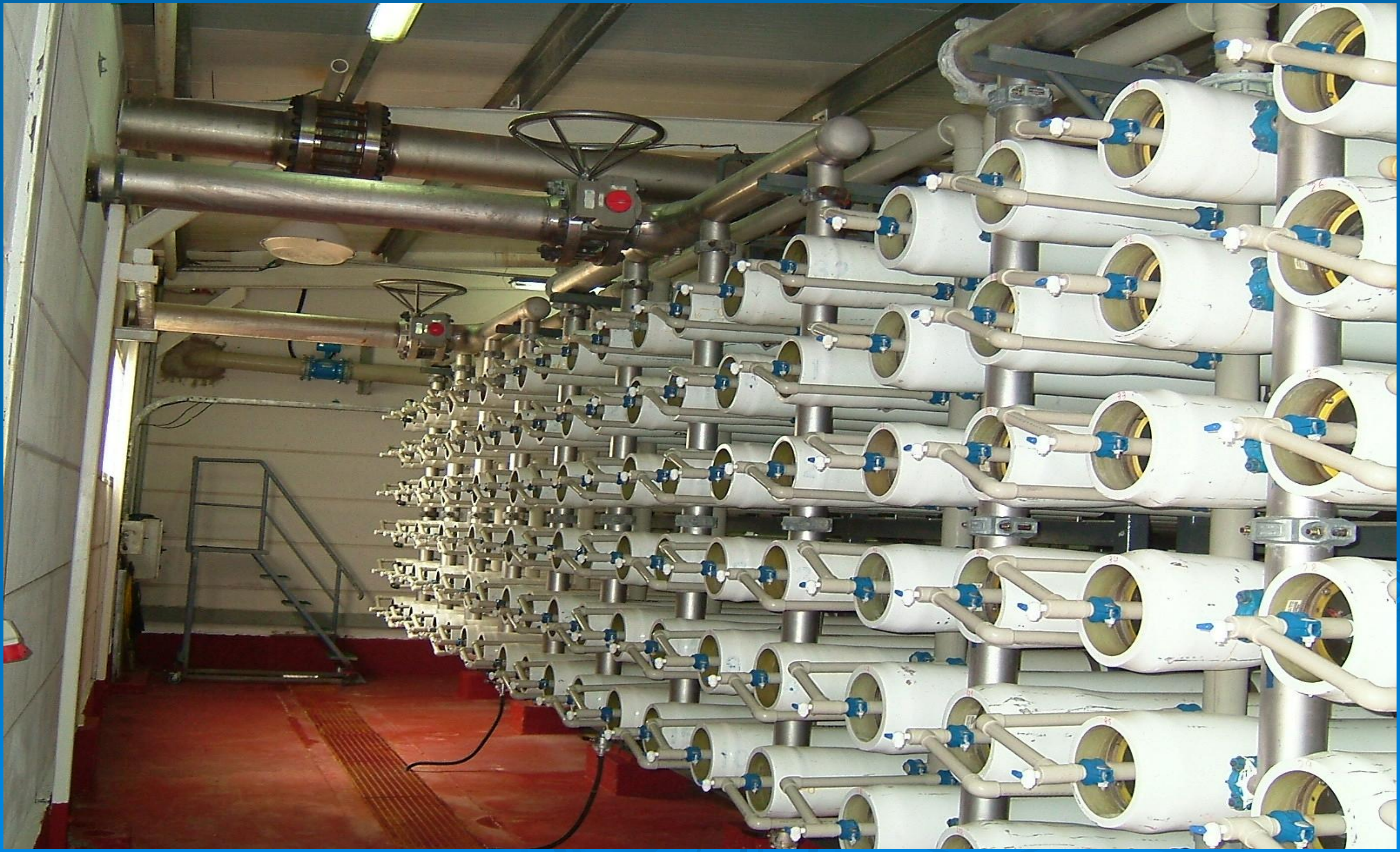
One HP Pump – Two RO Trains (Carboneras, Spain)

Three-Center RO System Configuration – 330 MLD Ashkelon SWRO Plant

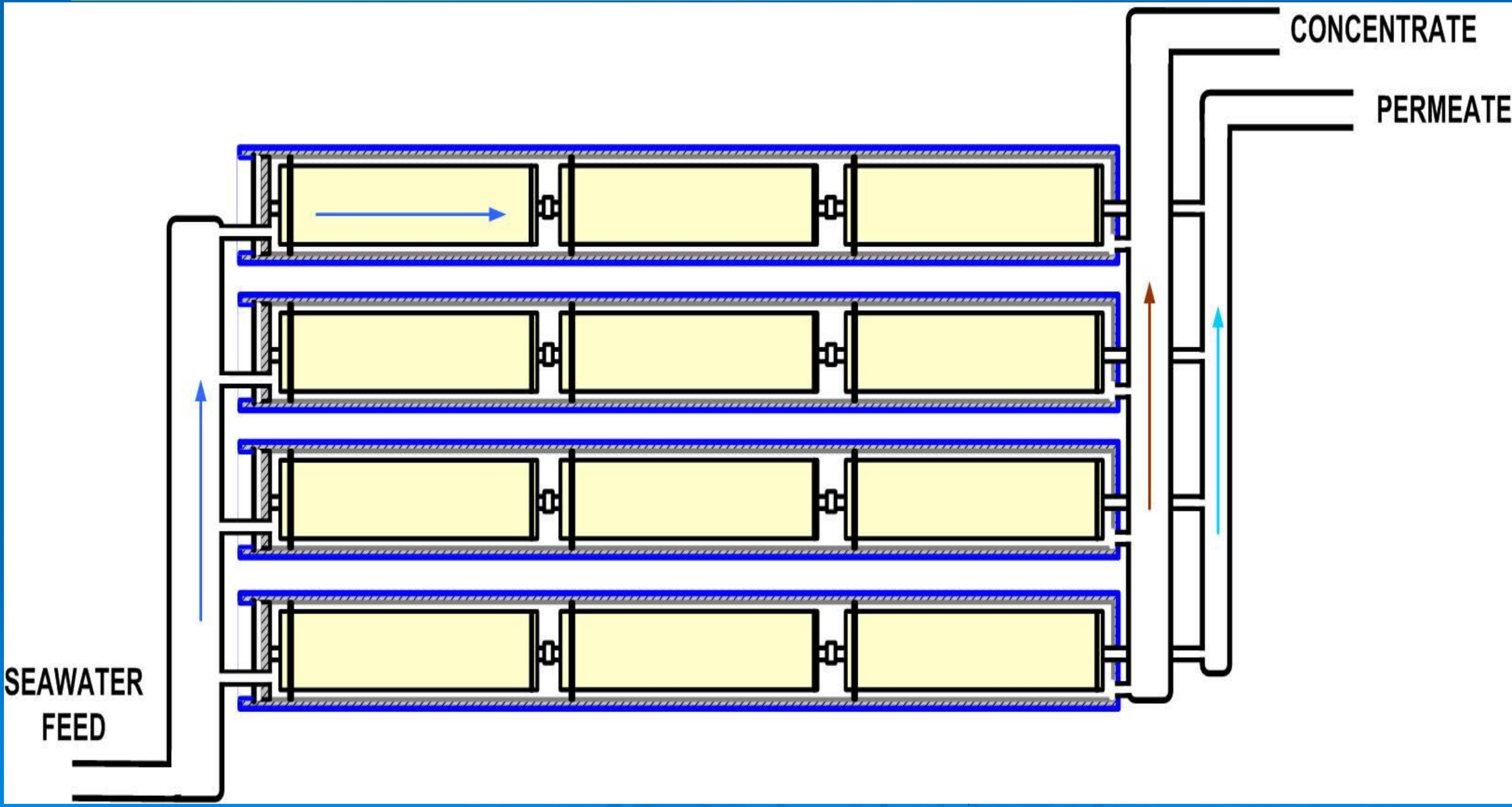


Courtesy: IDE

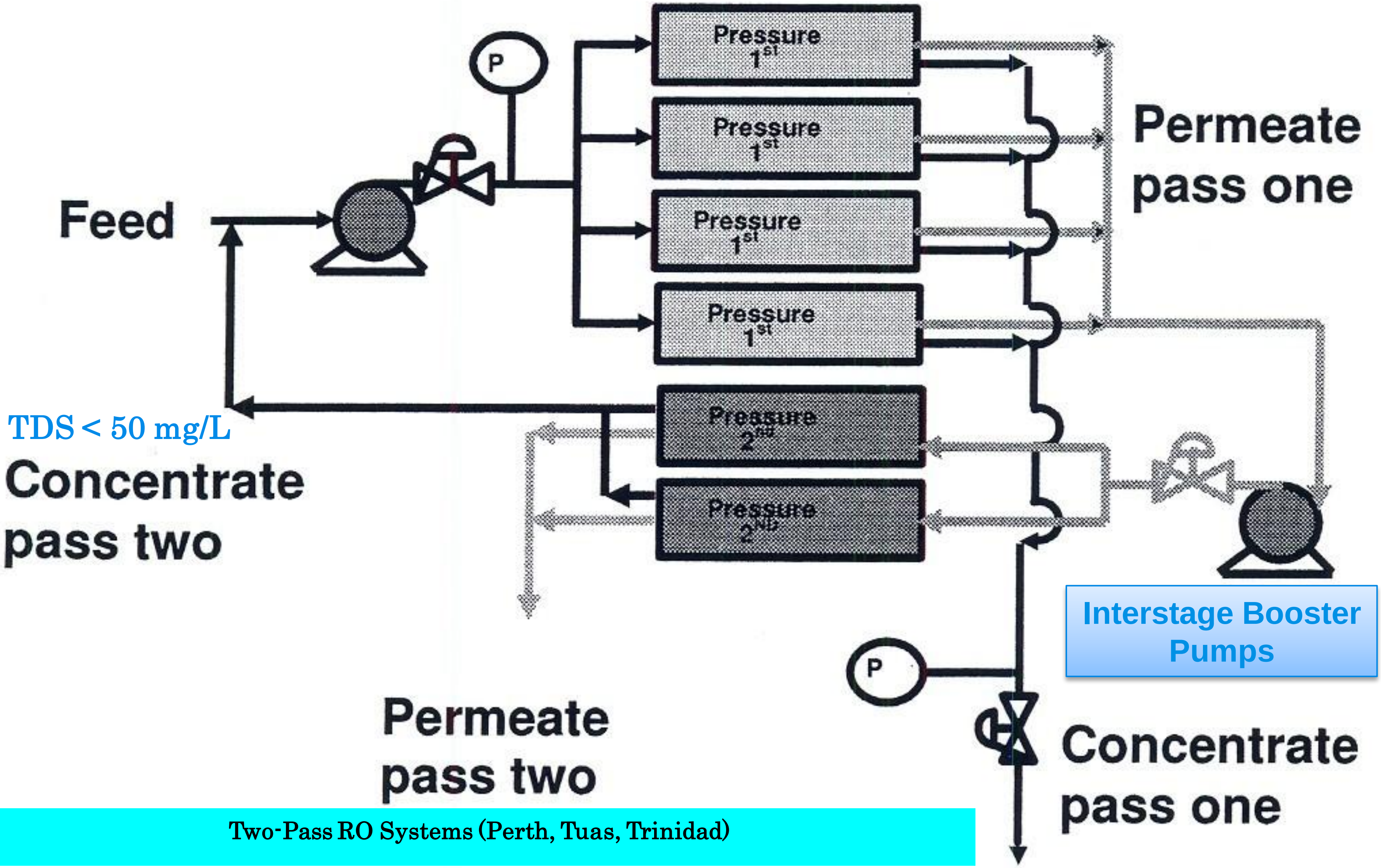
Alternative RO System Configurations



Single-Pass SWRO System



Two-Pass RO Systems

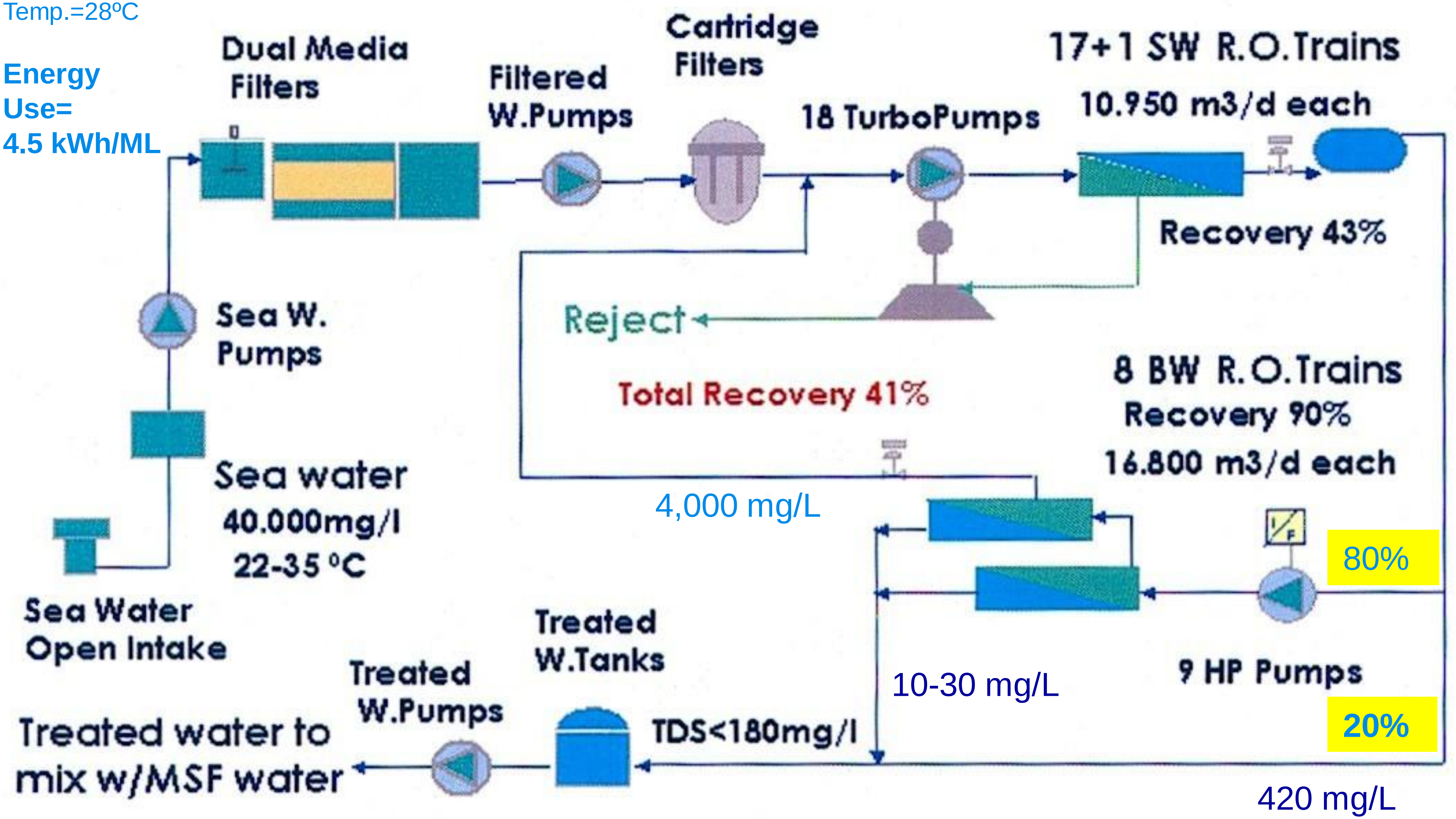


Two-Pass RO Systems (Perth, Tuas, Trinidad)

Partial Second Pass System
(Fujiarah SWRO Plant)

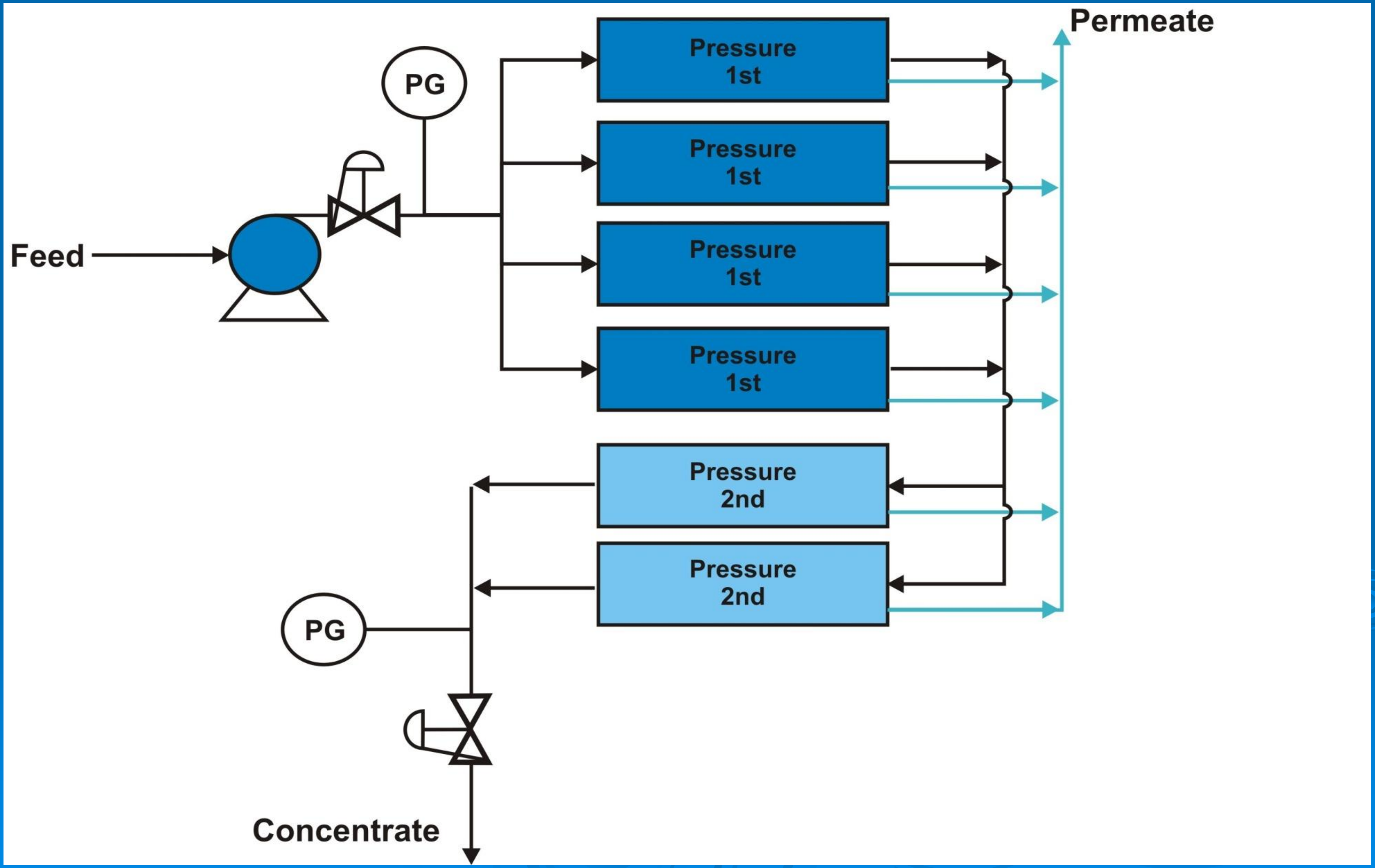
TDS =38.6 ppt
Temp.=28ºC

Energy Use= 4.5 kWh/ML



Source: Degremont

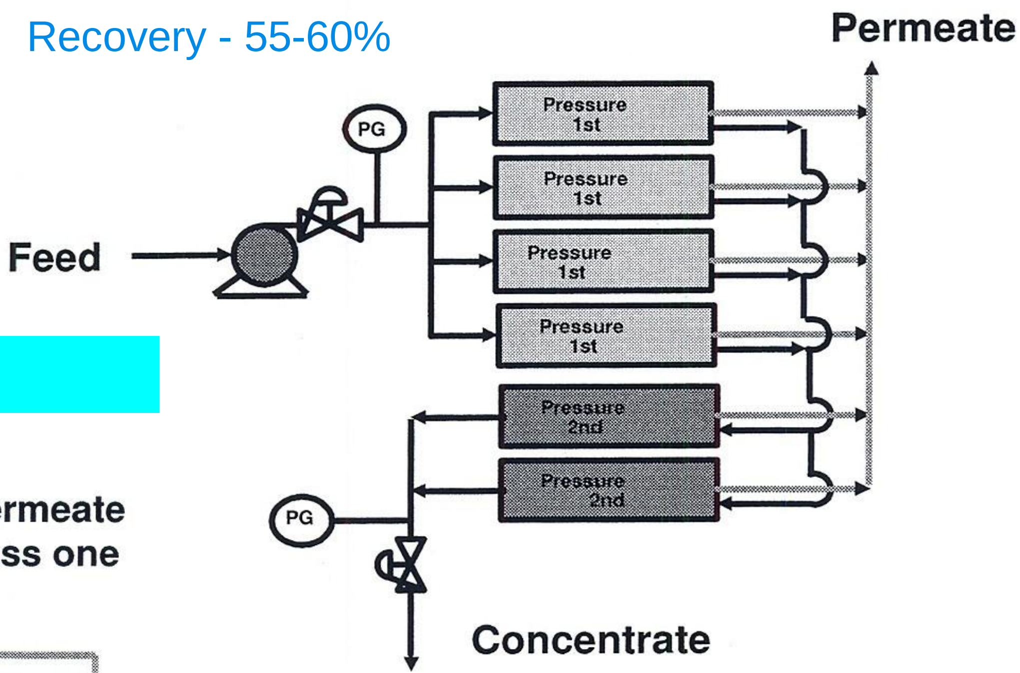
Two-Stage RO Systems



Two-Pass vs. Two-Stage RO Systems

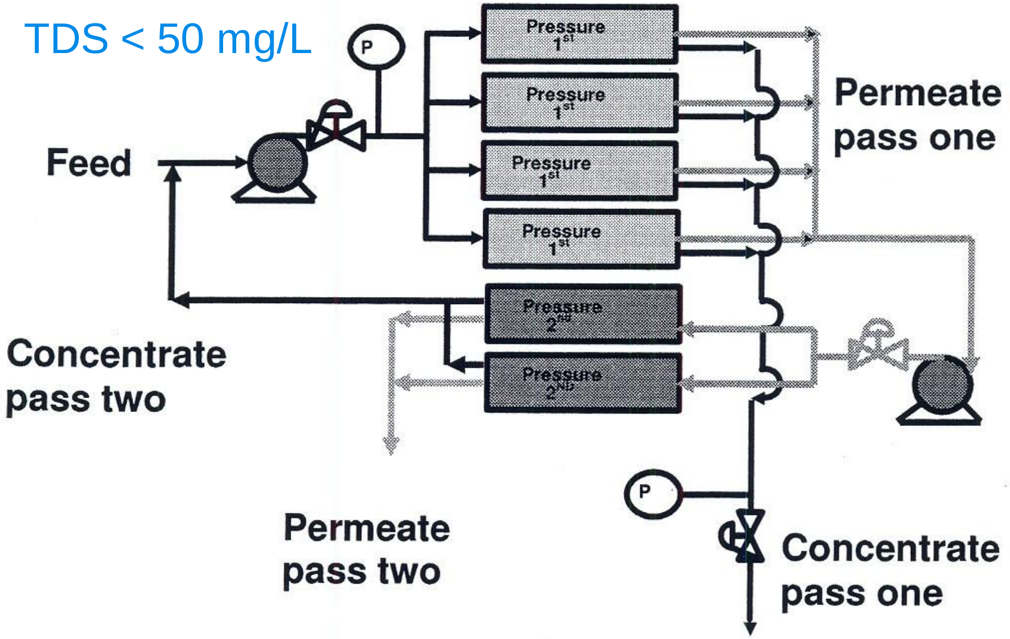
Two-Stage RO System (Mas Palomas)

Recovery - 55-60%



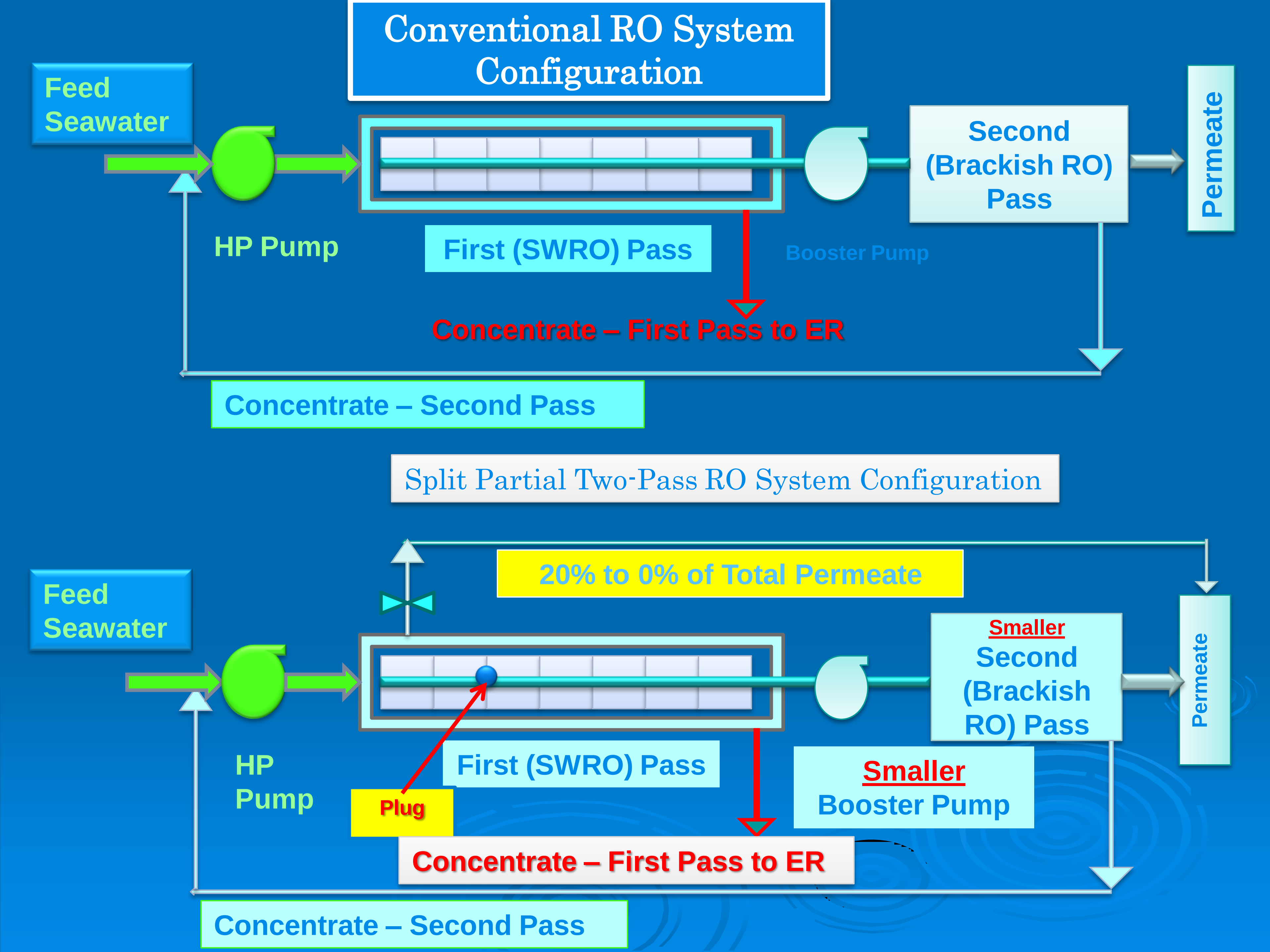
Two-Pass RO System (Trinidad)

TDS < 50 mg/L



Adding Extra Pass –
to Improve Water Quality

Adding Extra Stage –
To Produce More Water



Conventional RO System Configuration
Feed Seawater
HP Pump
First (SWRO) Pass
Booster Pump
Second (Brackish RO) Pass
Permeate
Concentrate – First Pass to ER
Concentrate – Second Pass
Split Partial Two-Pass RO System Configuration
20% to 0% of Total Permeate
Feed Seawater
HP Pump
First (SWRO) Pass
Plug
Smaller Second (Brackish RO) Pass
Smaller Booster Pump
Permeate
Concentrate – First Pass to ER
Concentrate – Second Pass

Product Water from Mediterranean Sea

Reverse Osmosis Permeate Water Quality

Seawater Source – Mediterranean Sea

Water Quality Parameter	Mediterranean Source Seawater Quality	Permeate Water Quality	
		Single Pass SWRO System	Split Partial Two Pass RO System
Temperature, ^0C	16-28	17-29	18-30
pH	8.1	6.3-7.2	7.9-8.1
Ca^{2+}, mg/L	480	1.0-2.0	0.35-0.45
Mg^{2+}, mg/L	1,558	1.9-2.8	0.5-1.0
Na^{+}, mg/L	12,200	98-196	15-34
K^{+}, mg/L	480	3.0-5.5	0.8-1.8
CO_3^{2-}, mg/L	5.6	0.0	0.0
HCO_3^{-}, mg/L	160	1.7-2.4	0.5-0.8
SO_4^{2-}, mg/L	3,190	2.9-6.3	1.4-2.95
Cl^{-}, mg/L	22,340	169-260	25-52
F^{-}, mg/L	1.4	0.7-1.1	0.5-0.8
NO_3^{-}, mg/L	0.00	0.00	0.00
B^{-}, mg/L	5.0	0.9-1.5	0.4-0.6
Br^{-}, mg/L	80	0.9-1.3	0.35-0.6
TDS, mg/L	**40,500**	**280-480**	**45-95**

Product Water from Arabian Gulf

Reverse Osmosis Permeate Water Quality Seawater Source – Arabian Gulf			
Water Quality Parameter	Persian Gulf Source Seawater Quality	Permeate Water Quality	
		Single Pass SWRO System	Split Partial Two Pass RO System
Temperature, ⁰C	18-35	19-36	20-37
pH	6.0 – 7.0	5.1-6.0	5.1-6.0
Ca^{2+}, mg/L	570	1.4-2.6	0.6-0.8
Mg^{2+}, mg/L	1,600	2.0-3.6	0.9-1.3
Na^{+}, mg/L	14,100	142-228	25-45
K^{+}, mg/L	530	4.3-6.8	1.5-2.2
CO_3^{2-}, mg/L	4.2	0.0	0.0
HCO_3^{-}, mg/L	155	1.8-2.3	0.6-0.9
SO_4^{2-}, mg/L	3,300	3.1-6.5	2.1-3.2
Cl^{-}, mg/L	24,650	222-305	37.5-64
F^{-}, mg/L	1.5	0.9-1.2	0.5-0.8
NO_3^{-}, mg/L	0.00	0.00	0.00
B^{-}, mg/L	6.3	1.3-2.5	0.7-1.0
Br^{-}, mg/L	83	1.2-1.5	0.60-0.80
TDS, mg/L	**45,000**	**380-520**	**70-120**

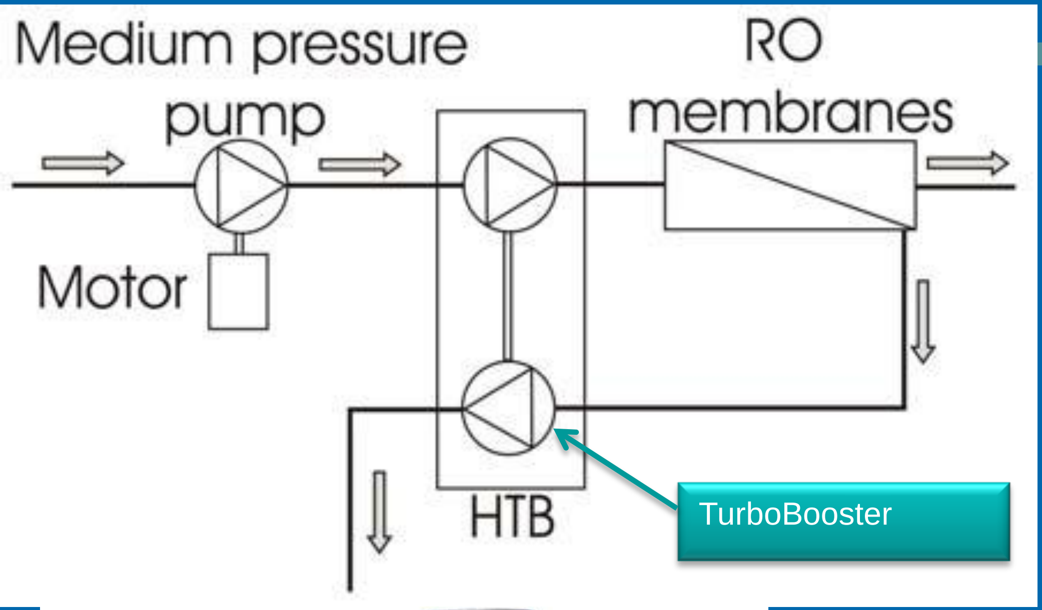
Product Water from the Red Sea

Reverse Osmosis Permeate Water Quality
Seawater Source – Red Sea

Water Quality Parameter	Red Sea Source Seawater Quality	Permeate Water Quality	
		Single Pass SWRO System	Split Partial Two Pass RO System
Temperature, ^0C	22-33	23-34	24-35
pH	7.0-8.0	6.8-7.8	7.6-8.0
Ca^{2+}, mg/L	500	1.1-2.1	0.5-0.7
Mg^{2+}, mg/L	1,540	1.8-3.4	0.7-1.0
Na^{+}, mg/L	13,300	142-220	20-38
K^{+}, mg/L	489	3.2-6.5	1.2-1.8
CO_3^{2-}, mg/L	2.4	0.0	0.0
HCO_3^{-}, mg/L	142.4	1.4-2.0	0.5-1.0
SO_4^{2-}, mg/L	3,100	2.8-6.2	1.9-2.6
Cl^{-}, mg/L	22,840	195-276	29-58
F^{-}, mg/L	0.9	0.5-0.7	0.3-0.5
NO_3^{-}, mg/L	0.00	0.00	0.00
B^{-}, mg/L	5.3	1.2-1.7	0.45-0.80
Br^{-}, mg/L	80	1.0-1.4	0.45-0.60
TDS, mg/L	**42,000**	**350-520**	**55-105**

Energy Recovery Systems

Hydraulic Turbocharger



Courtesy: PEI

- Turbocharger Popular for Small and Medium Size Plants (20 to 40 % pressure boost).
- Available for Low & High Pressures.
- Used for High-Recovery (Brine Conversion) Systems to Achieve 60 – 65 %.
- Low Maintenance & Brine Leakage Into Feed Stream.
- Lower Cost and Space Requirements than Other Energy Recovery Systems.

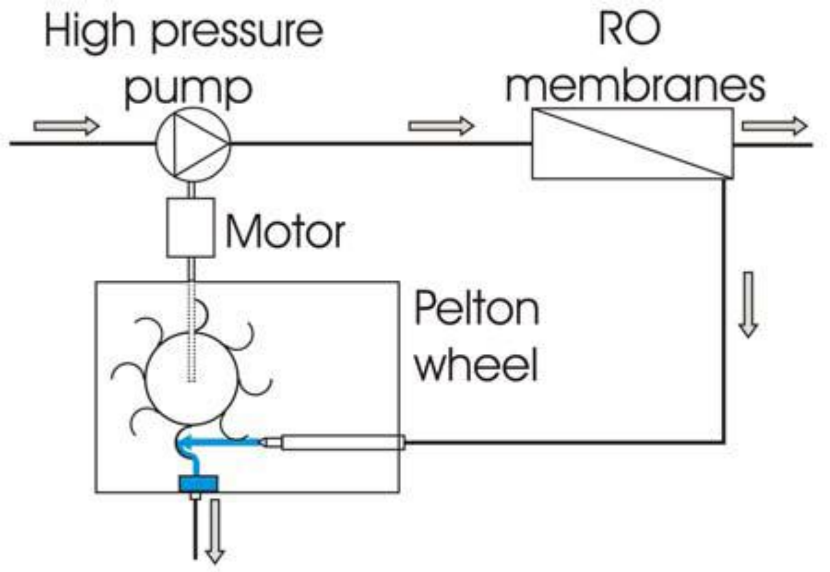
Hydraulic Turbocharger – Large Installations (2.35 to 2.65 kWh/m³)

Pump Efficiency ~ $n \times (Q/H)^{0.5} \times (1/H)^{0.25}$

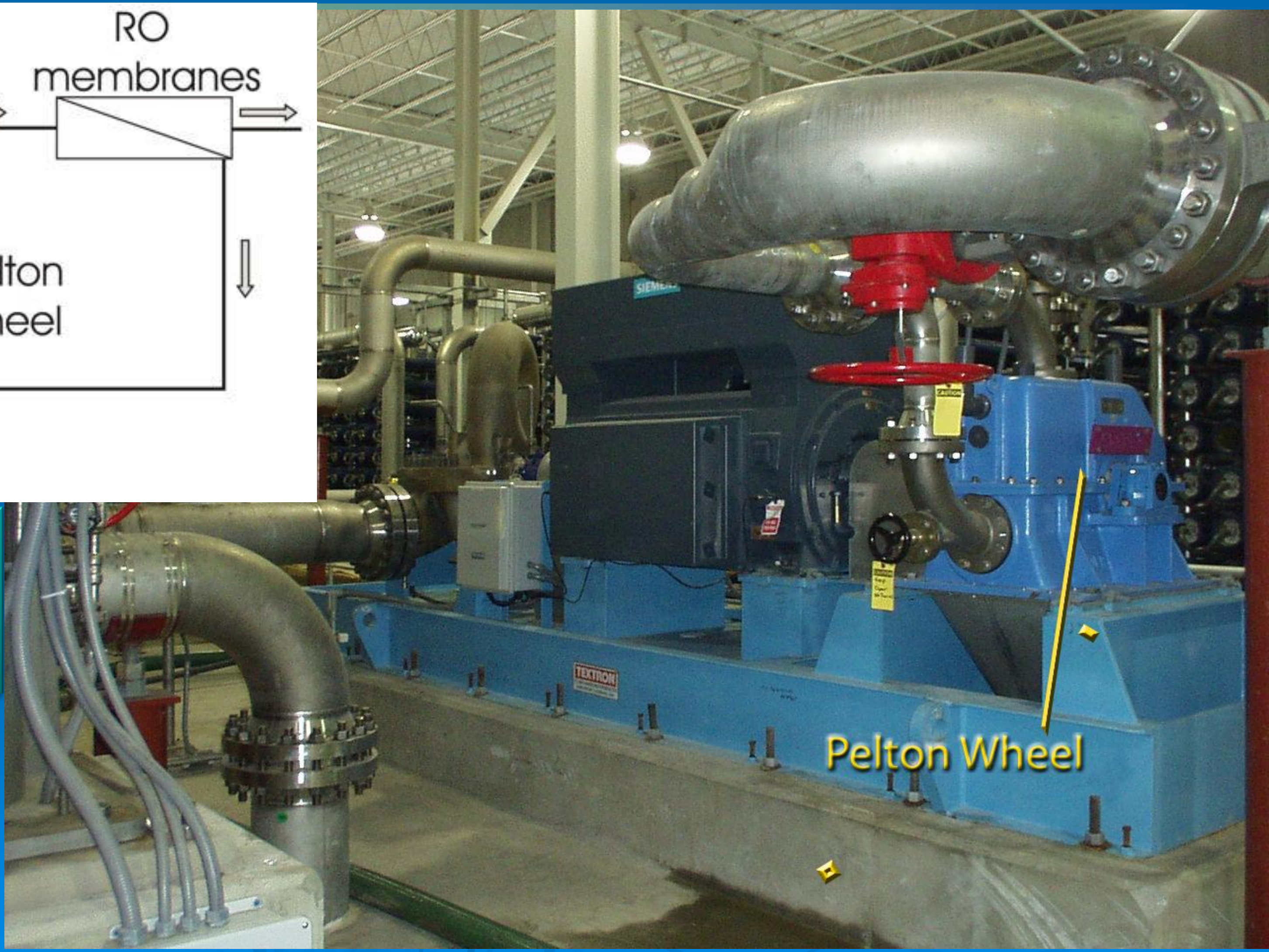
- **114 ML/d Plant in Jebel Ali, UAE**
  - **9 RO Trains;**
  - **16 Single-stage HP RO Pumps;**
  - **Up to 525 psi (40 bars) of Boost;**
  - **HP RO Pumps Operating @ Full Flow @ ½ Pressure –**

    5-7 % Extra Efficiency.
- **35 ML/d Plant in Thailand (PT Chemicals) – 2.6 kWh/m³.**
- **145 ML/d NEWater Ulu Pandan Plant, Singapore**

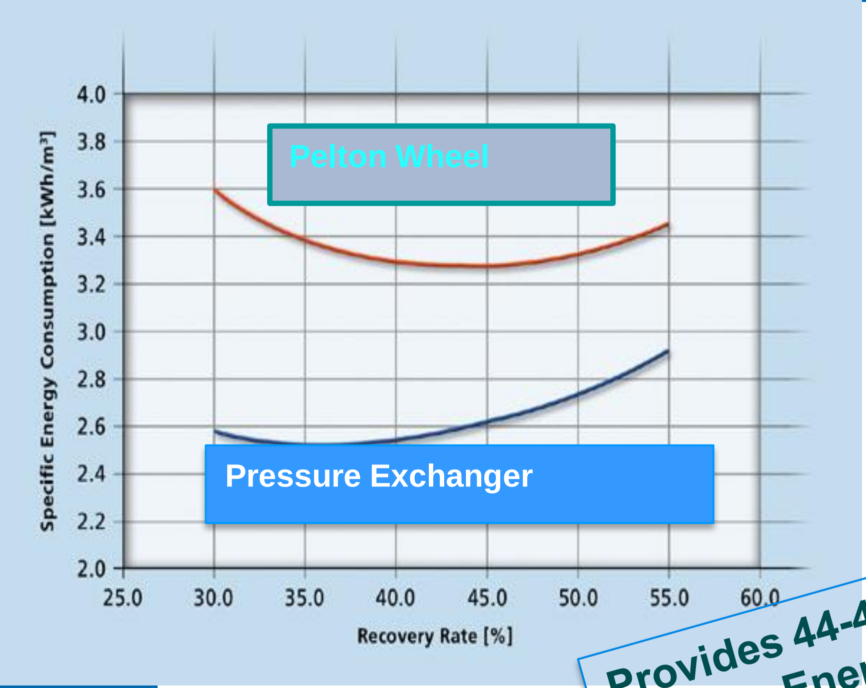
Pelton Wheels – Majority of Existing Plants

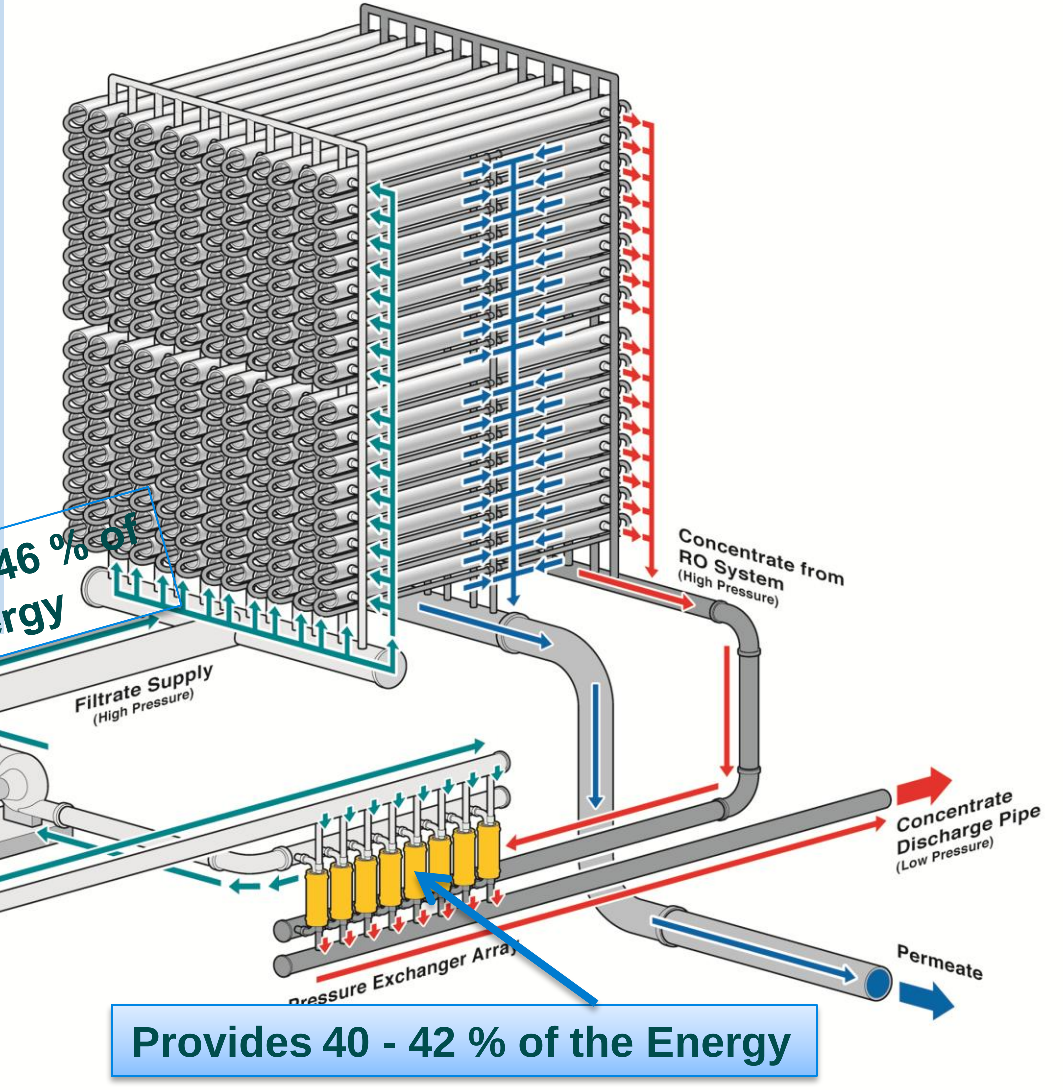


Conversion Efficiency: 80 to 90 %

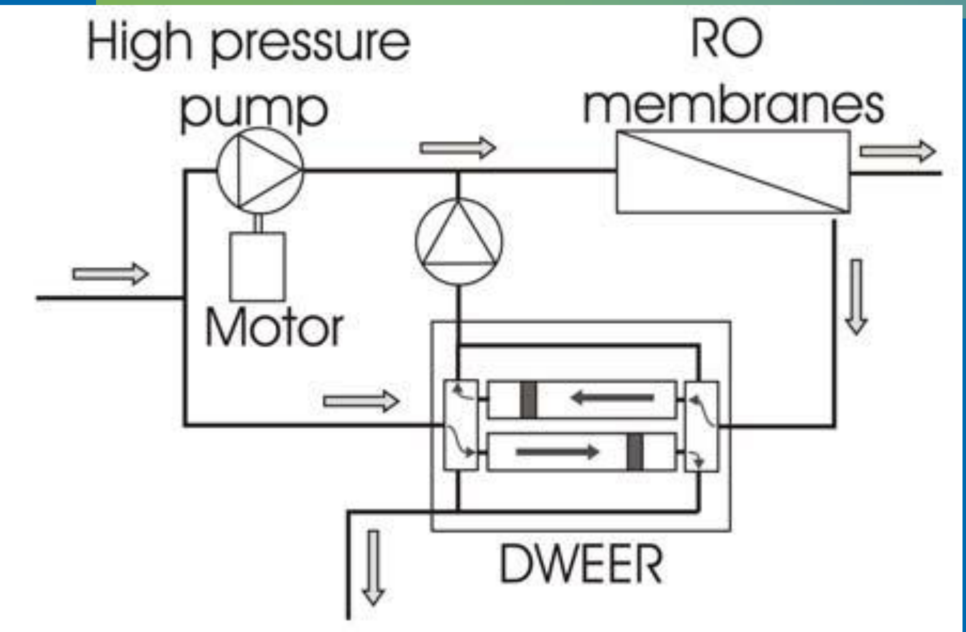


Pressure Exchangers Allow the Use of Larger Pumps/RO Trains





DWEER and ERI Pressure Exchangers

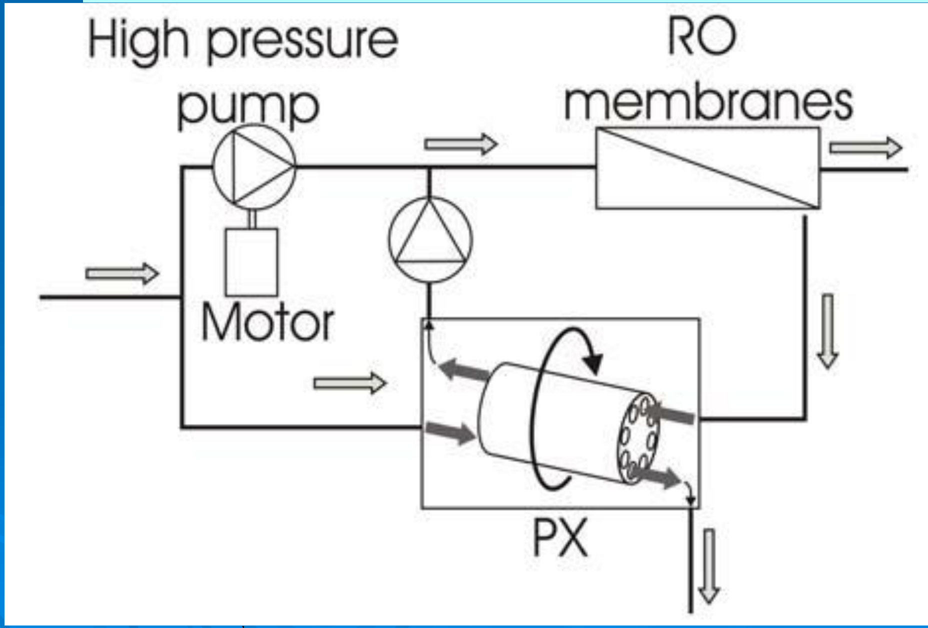


ERI PX Pressure Exchanger

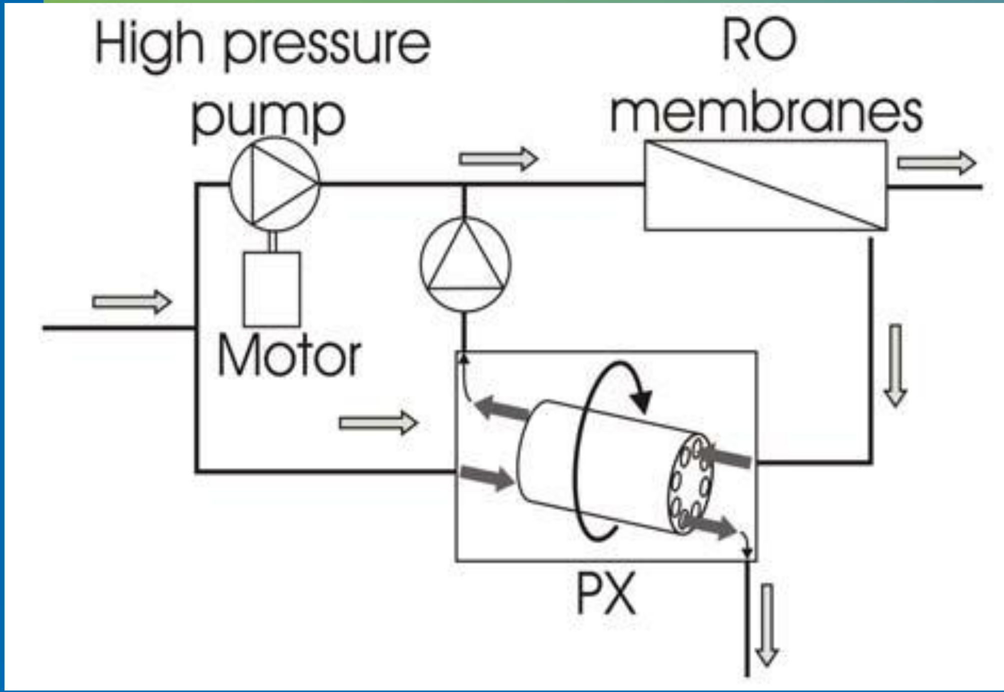
- 96% Energy Conversion Eff.
- Smaller Footprint;
- One Moving Part – Shaftless Rotor;
- Rotor Hydrostatically Suspended in Ceramic Sleeve.

DWEER Exchanger

- Positive Displacement Pistons Instead of Rotor;
- LinX Valves Cause the Two Vessels to Exchange Functions before The Piston Completes Stroke.



ERI System – Current Status



- Largest In Operation - Hamma (Algeria) – 190 ML/d;
- Largest in Construction – Hadera (Israel) – 275 ML/d;
- Base Unit – PX 220;
  (1.4 ML/d) in ops since 2002;
- 10 to 16 Units per RO Train
  (9.5 – 15 ML/d RO Train).
- Challenges:
  - **Mixing – 5 to 7%;**
  - **Efficiency Decreases w/ Increase in Plant Recovery.**

DWEER System – Current Status

- Used in Ashkelon (330 ML/d), and Singapore (130 ML/d);
- 5 ML/d SWRO Train – One DWEER System – Model 1100;
- Ashkelon – 2 x 40 DWEER 2200 Systems;
- RO w/ DWEER – 0.5 to 0.7 kWh/M3 Less Energy than Pelton Wheel @ (45 % Recovery).

Tuas, Singapore
Triple DWEER 1100
15 ML/d SWRO Trains

DWEER – Recent Large Projects

- Gold Coast, Australia – 133 ML/d
- Sydney, Australia – 125/250 ML/d
- Aguilas, Spain – 180 ML/d

Calder AG (Flowserve) – DWEER GA

- 25 % Higher Capacity Than DWEER 1100
- FRP Instead of Steel Vessels
- New LinX Valve With Two Seal Rings for Lowest Leakage
- Specific Power Consumption Losses Reduced by 26 %

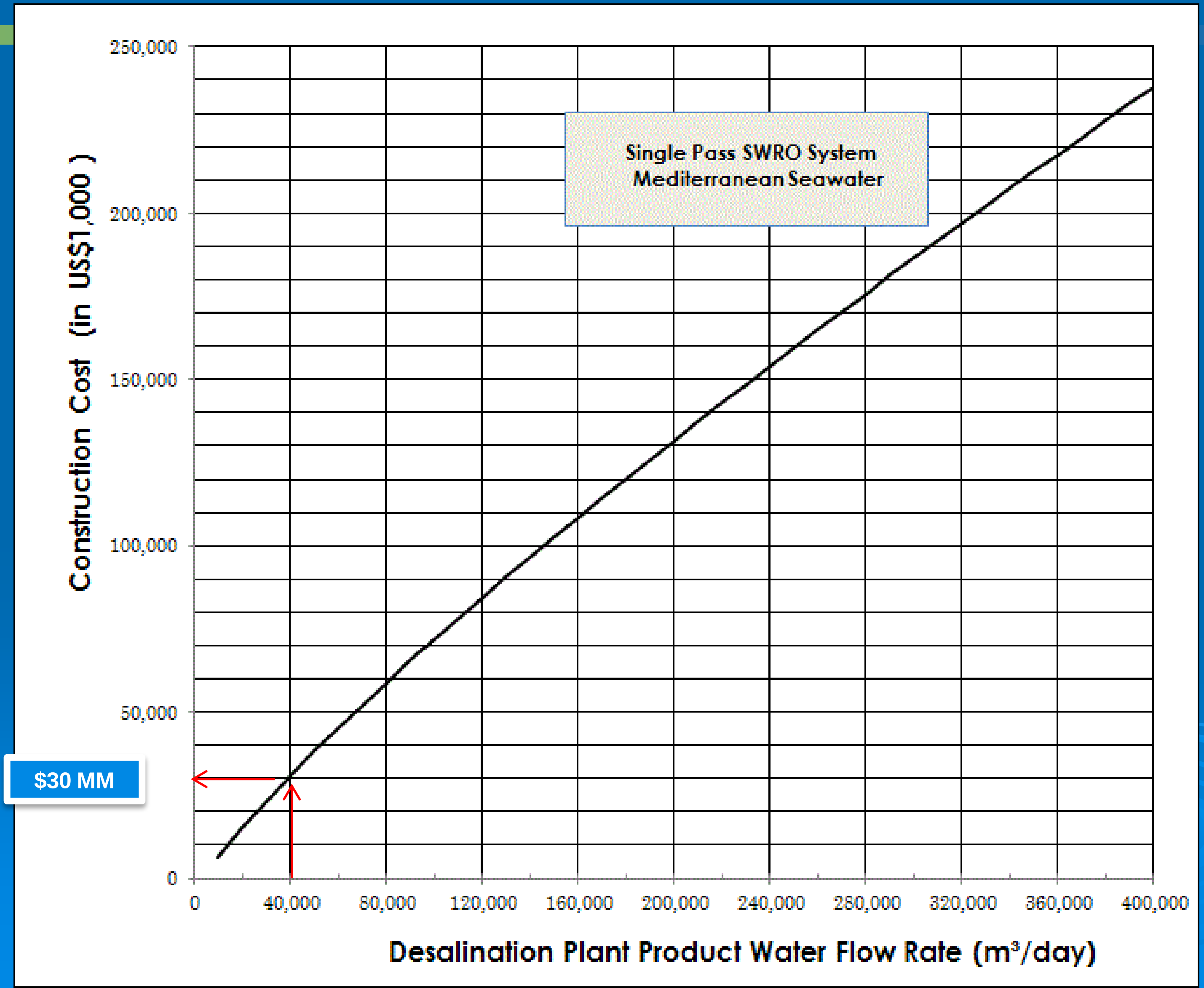
SWRO System Construction Costs

- Dependent on Source Water Quality & Target Product Water Quality
- Usually Between US$300 and 1,000/$m^3$/day
- Single-stage/Single Pass SWRO System is Least Costly
- Additional Costs for Two-Pass/Two-Stage RO System May Vary Between 15 and 30 % of the These of Single Pass/Single Stage SWRO System

Costs of Key RO System Components

Item	Construction Cost (US$/item or as indicated)
8-inch Brackish RO Membrane Elements	US$250 – US$350/element
8-inch SWRO Membrane Elements	US$400 – US$600/element
16-inch SWRO Membrane Elements	US$2,800 – US$3,300/element
Brackish RO Pressure Vessels for 8-inch Elements	US$1,000 – US$1,300/vessel
SWRO Pressure Vessels for 8-inch Elements	US$1,300 – US$1,800/vessel
SWRO Pressure Vessels for 16-inch Elements	US$3,600 – US$5,000/vessel
RO Train Piping	US$250,000 – US$750,000/RO Train
RO Train Support Frame	US$150,000 – US$550,000/RO Train
RO Train Instrumentation and Controls	US$30,000 – US$150,000/RO Train
High Pressure Pumps	US$150,000 – US$2,400,000/RO Train

RO System Construction Cost – Single Pass Mediterranean Water



Source Water Quality – Cost Impacts

Seawater Source	Unit Construction Costs	Unit O&M Costs	Unit Water Costs
Mediterranean	1.0	1.0	1.0
Gulf of Oman	1.09	1.07	1.08
Red Sea	1.12	1.10	1.11
Arabian Gulf	1.16	1.14	1.15

Effect of Product Water Quality on RO System Costs

Effect of Target Product Water Quality on Water Costs

Target Product Water Quality	Construction Costs	O&M Costs	Cost of Water	
TDS = 500 mg/L Chloride = 250 mg/L Boron = 1 mg/L Bromide = 0.8 mg/L	1.00	1.00	1.00	Single Pass RO System
TDS = 250 mg/L Chloride = 100 mg/L Boron = 0.75 mg/L Bromide = 0.5 mg/L	1.15 – 1.25	1.05 – 1.10	1.10 – 1.18	Partial Second Pass RO System
TDS = 100 mg/L Chloride = 50 mg/L Boron = 0.5 mg/L Bromide = 0.2 mg/L	1.27 – 1.38	1.18 – 1.25	1.23 – 1.32	Full Two-Pass RO System
TDS = 30 mg/L Chloride = 10 mg/L Boron = 0.3 mg/L Bromide = 0.1 mg/L	1.40 – 1.55	1.32 – 1.45	1.36 – 1.50	Full Two-Pass RO System + IX

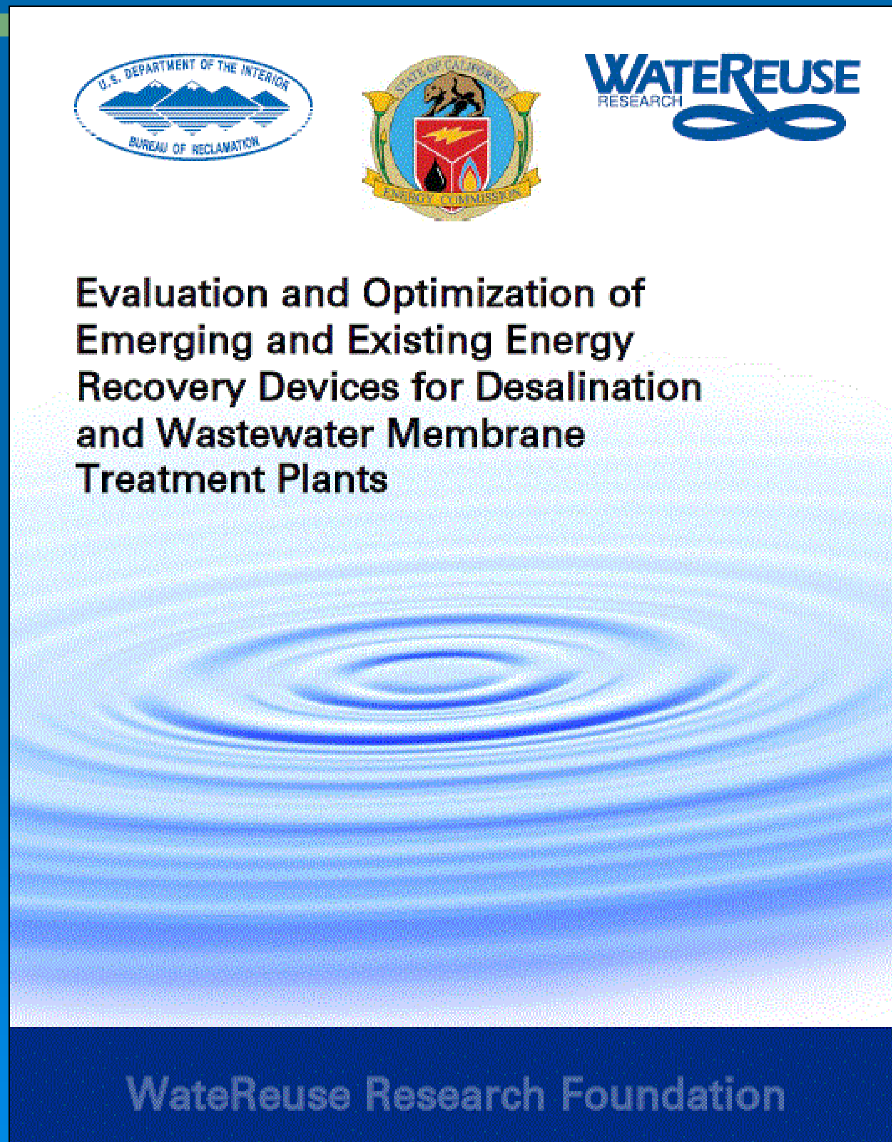
Example of SWRO Cost Estimates for 40 MLD Plant

- Construction Cost of Single-Pass 40 MLD SWRO System using Mediterranean Seawater = US$30 MM (see RO Cost Graph)

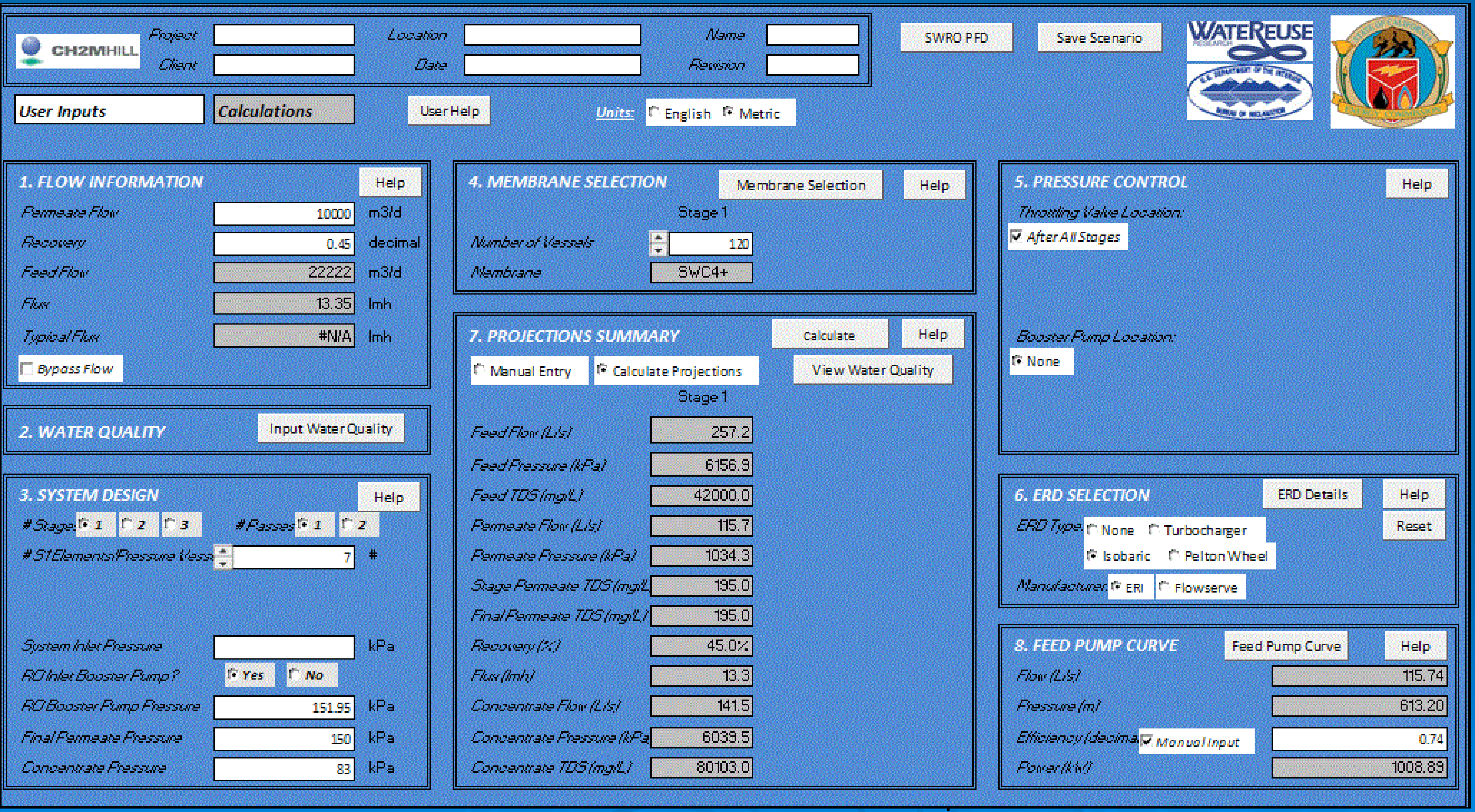
- Construction Cost of Single-Pass 40 MLD SWRO System using Arabian Gulf Seawater = US$30 MM x 1.16 = US$34.8 MM

- Construction Cost of Two-pass 40 MLD SWRO System Using Arabian Gulf Seawater = US$34.8 x 1.3 = US$45.24 MM

New Software for ERD Selection and Cost Estimating



Software Input



ERD Selection and Cost Estimate

Isobaric Energy Recovery Device

Help | Summary Sheet

Device Information

Select Device	○ *Dweer* ◉ *PX*
Model	PX-300
Manufacturer	Energy Recovery Inc.
Application	SWRO
Efficiency	96%
Max Working Pressure (kPa)	8274
Min Flow (L/s)	12.62
Max Flow (L/s)	18.93
Salinity Leakage (%)	2.81%
Min Concentrate Pressure (kPa)	83
Cost	**$ 35,000**
User-Override Cost	

System Information

# of Devices per Train	8	#
Train Feed Flow	257.20	L/s
Concentrate Flow	141.46	L/s
Isobaric Feed Flow per Device	17.54	L/s
LP Concentrate Pressure	83	kPa
HP Concentrate Pressure	6039.47	kPa
System Feed Pressure	152	kPa
Stage 1 Feed Pressure	6156.85	kPa
Boosted Pressure	**5798.37**	kPa
Circulation Pump Needed?	Yes	Y/N
Circulation Pump Pressure	358	kPa
Interstage Booster Pump Needed?	No	Y/N

Questions and Discussions