CornellEngineering
Civil and Environmental Engineering

CEE 4540

Sustainable municipal drinking water treatment

Topic: Desalination

Instructor: YuJung Chang

YuJung.Chang@aecom.com

Class #16 10/24/2018 2:55 – 4:10pm

Desalination - Seawater

Homework: Provide Basic Design for a Seawater RO (SWRO) Membrane Plant (Due 10/31)

- Capacity: 20 MGD
- Assumptions:
  - Membrane Production Flux: 8 gfd
  - TDS: 32,000 mg/L
  - 7 RO elements in each RO vessel
  - No more than 9 Height (9 membrane vessels in vertical direction in each skid)
  - No more than 50 membrane Vessels per skid
  - 10% Redundancy

Your Design:

- Select a SWRO Membrane from Dow’s product line (an example shown below)
  - Provide reasons/benefits for the RO element selection
  - Determine how many membrane elements needed
  - Determine how many RO Trains needed
- How many membrane elements needed?
- How many RO skids required?
- Determine Osmotic Pressure for the raw seawater
- https://www.dow.com/en-us/markets-and-solutions/products/dowfilmtecseawaterreverseosmosis8elements/DOWFILMTECSW30HRLE440i

Seawater Desalination
It’s Past, Present, and Future

Seawater Desalination: Historical Perspective

- Desalination has been practiced since ancient times
- Used by explorers since the since the early 1600’s
- Commercial scale thermal desalination used since World War II
- Rapid increase in membrane desalination in recent years

Seawater Desalination: Historical Perspective

– It has always been the most expensive way to produce drinking water at the commercial scale (<u>and still is</u>):

- High Planning & Permitting costs
- High Capital Costs
- High Operation & Maintenance Costs

Seawater Desalination: Historical Perspective

– Historically, seawater desalination has therefore been practiced almost exclusively in areas that are:

- Close to the ocean (duh !)
- With very low annual rainfall
- With abundant and/or low cost energy
- Example: The Middle East

Seawater Desalination: A Solution to the World’s Water Crisis ?

- New Global Influences are changing this situation:
  - Global warming…..severe drought conditions becoming more common (e.g. Australia, Spain)
  - Approximately 50% of the world’s population live within 200 km of the coast
  - Many of the world’s largest and fastest growing cities are near the coast
  - More people move to coastlines (both younger & older generation)

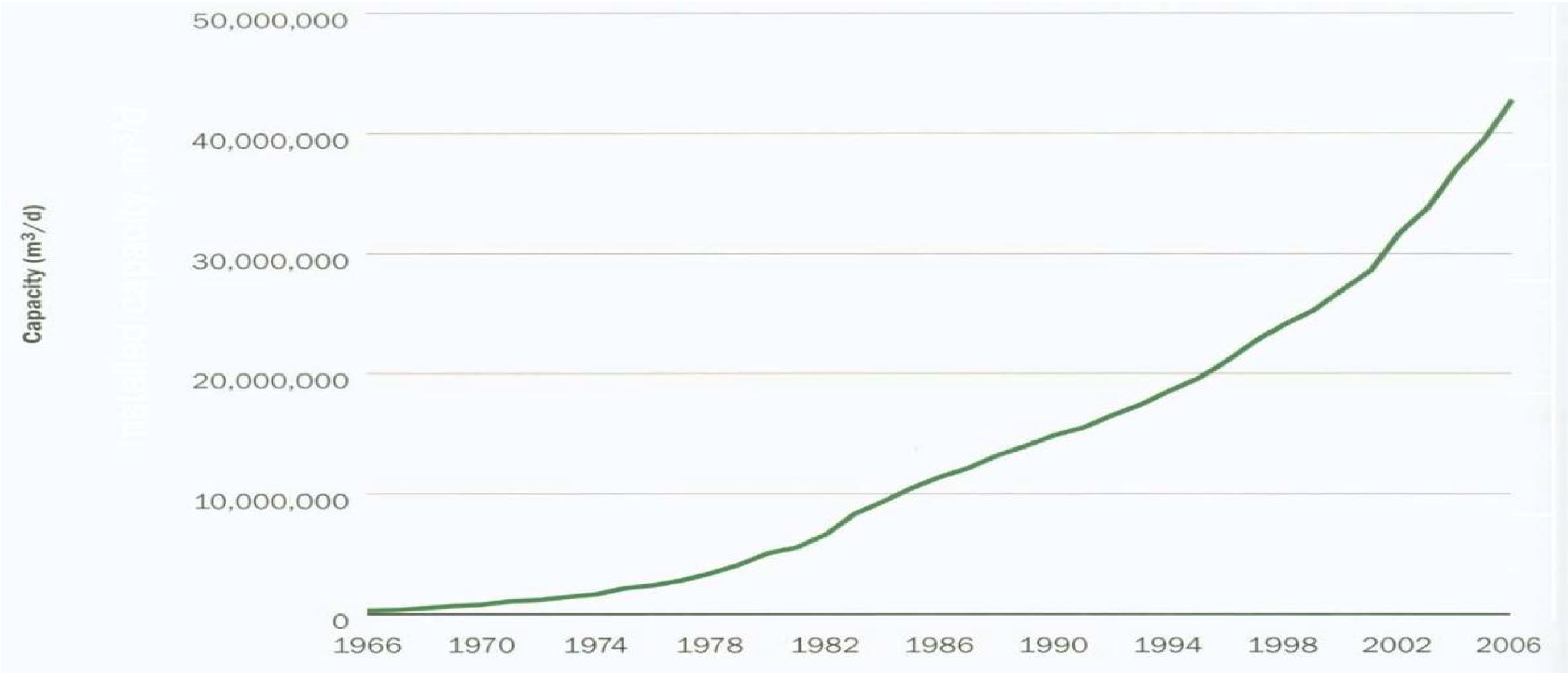
Seawater Desalination
A Solution to the World's Water Crisis ?

- Available, lower cost water sources are nearing or at exhaustion in many areas
- Desalination has been gradually getting cheaper
- Seawater desalination is growing astronomically on a global scale

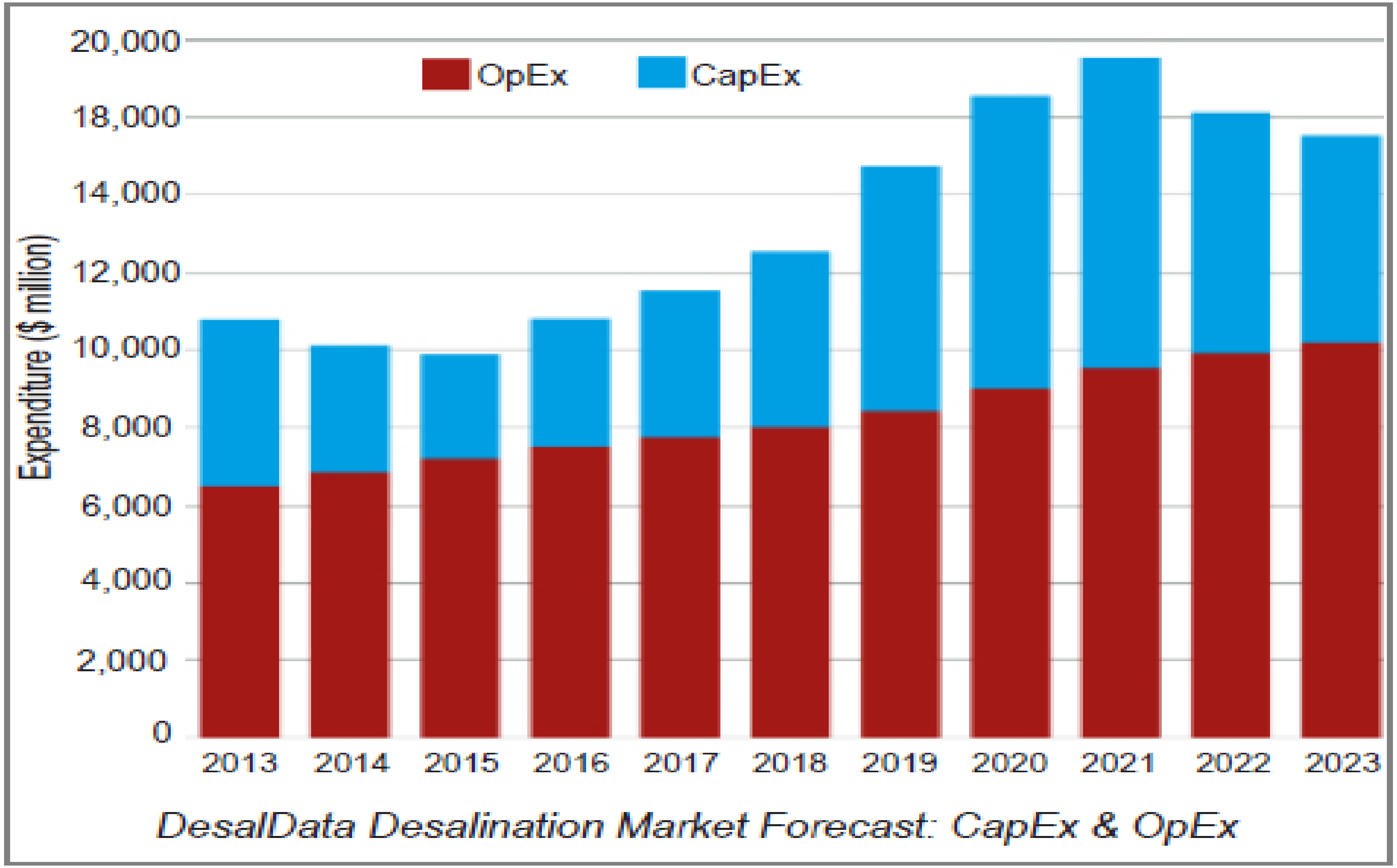
Applications for SWRO

- Desalination for municipal costumers (e.g., Tampa Bay, FL; Carlsbad, CA)
- Industrial applications (mining industry, power generation, etc.)
- Water Reuse (treating wastewater treatment plant effluent)

World Installed Desalination Capacity (1966 through 2006)



Global Desalination Market



Seawater Desalination – The Basics

- Seawater desalination is achieved on the commercial scale in two main ways:
  - Thermal Processes, where water is evaporated, then condensed, leaving impurities behind
  - Membrane Processes, where contaminants are removed from water to purify it
- The specific process used in a Project is highly dependent on site specific variables:
  - Seawater salinity
  - Seawater quality (TOC, Algae, biological activities, etc.)
  - The cost of electrical power
  - Co-location with wastewater treatment plant, heavy industry and/or power plants

Seawater Desalination Technologies

Thermal Technologies

- Multiple Effect Distillation (MED)
- Multi-Stage Flash Distillation (MSF)
- Mechanical Vapour Compression (MVC)
- Thermal Vapour Compression (TVC)
- Absorption Vapour Compression (AVC)
- Solar Distillation (SD)

Membrane Technologies

- Reverse Osmosis (RO)
- 2-Stage Nanofiltration (NF)

Seawater Desalination Technologies

Thermal Technologies

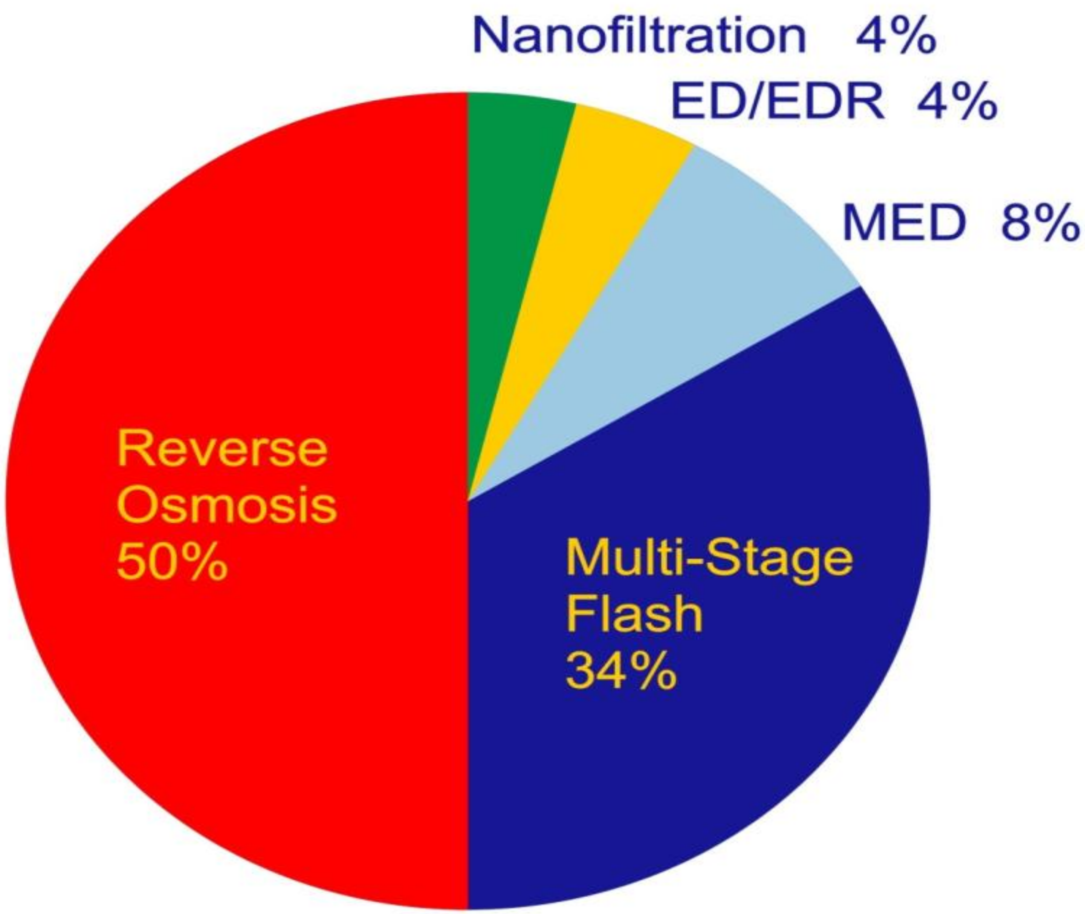
- Multiple Effect Distillation (MED)
- Multi-Stage Flash Distillation (MSF)
- Mechanical Vapour Compression (MVC)
- Thermal Vapour Compression (TVC)
- Absorption Vapour Compression (AVC)
- Solar Distillation (SD)

Membrane Technologies

- Reverse Osmosis (RO)
- 2-Stage Nanofiltration (NF)

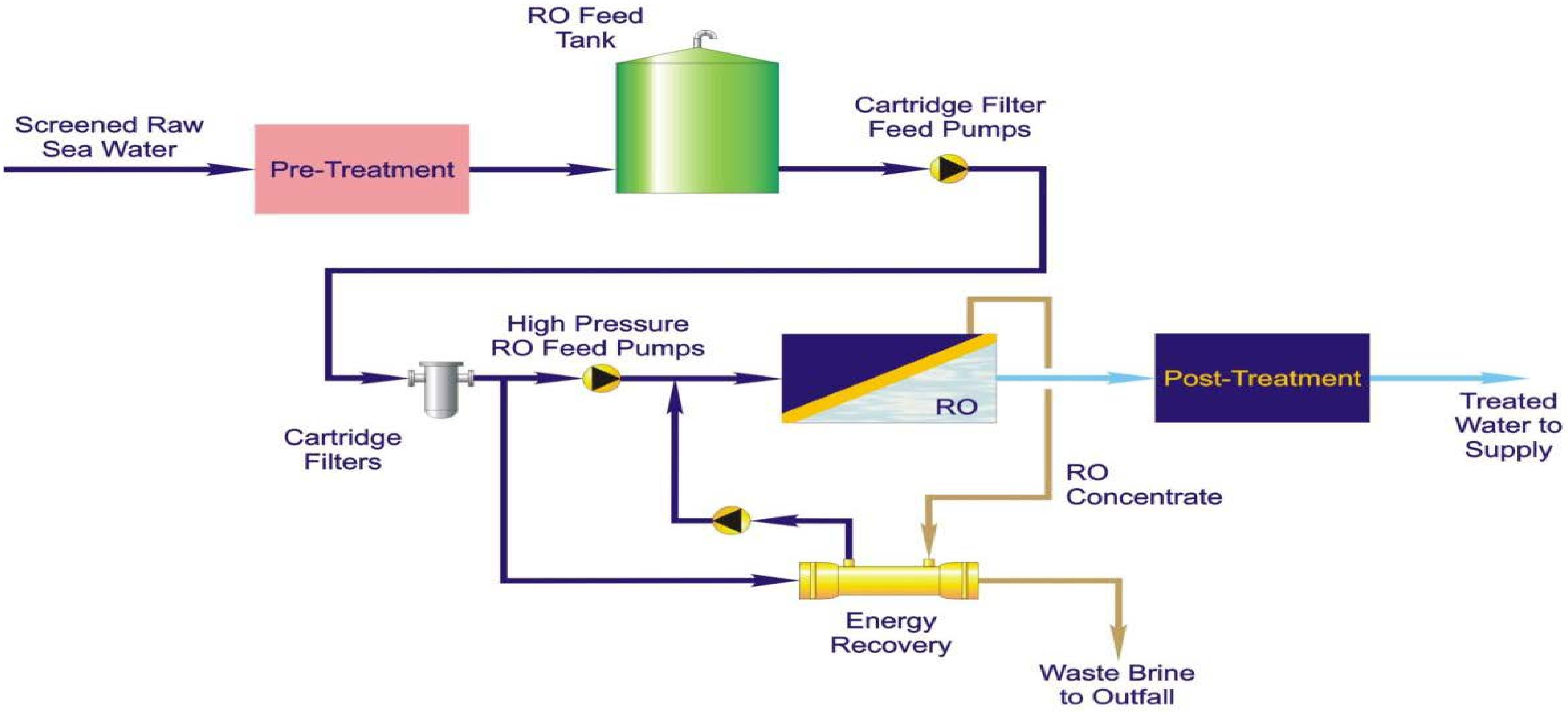
Installed Capacity, by Process

- RO and MSF dominate the industry
- Highest total capacity for non-RO seawater desalination is MSF



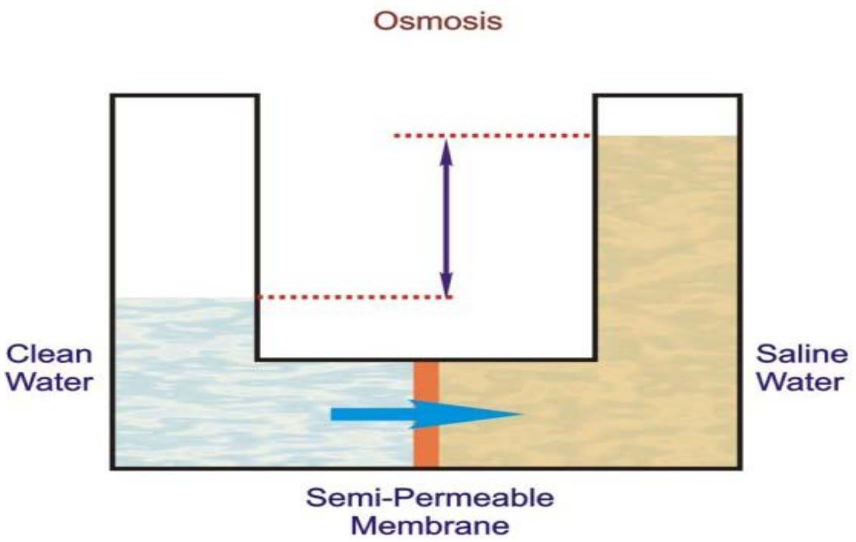
Seawater Desalination Fundamental Principles

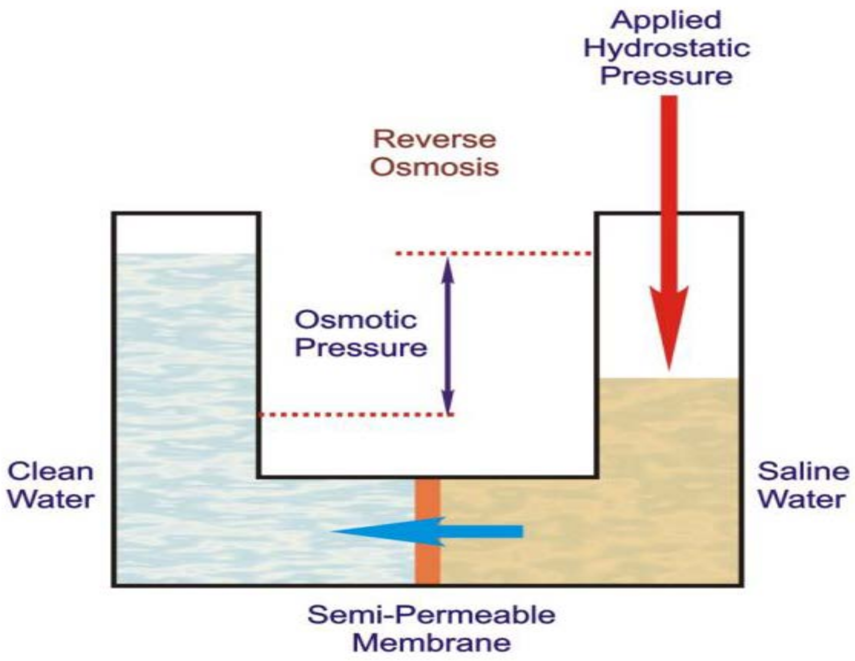
Typical PFD for Seawater Reverse Osmosis (SWRO)



Reverse Osmosis: The Basic Principle

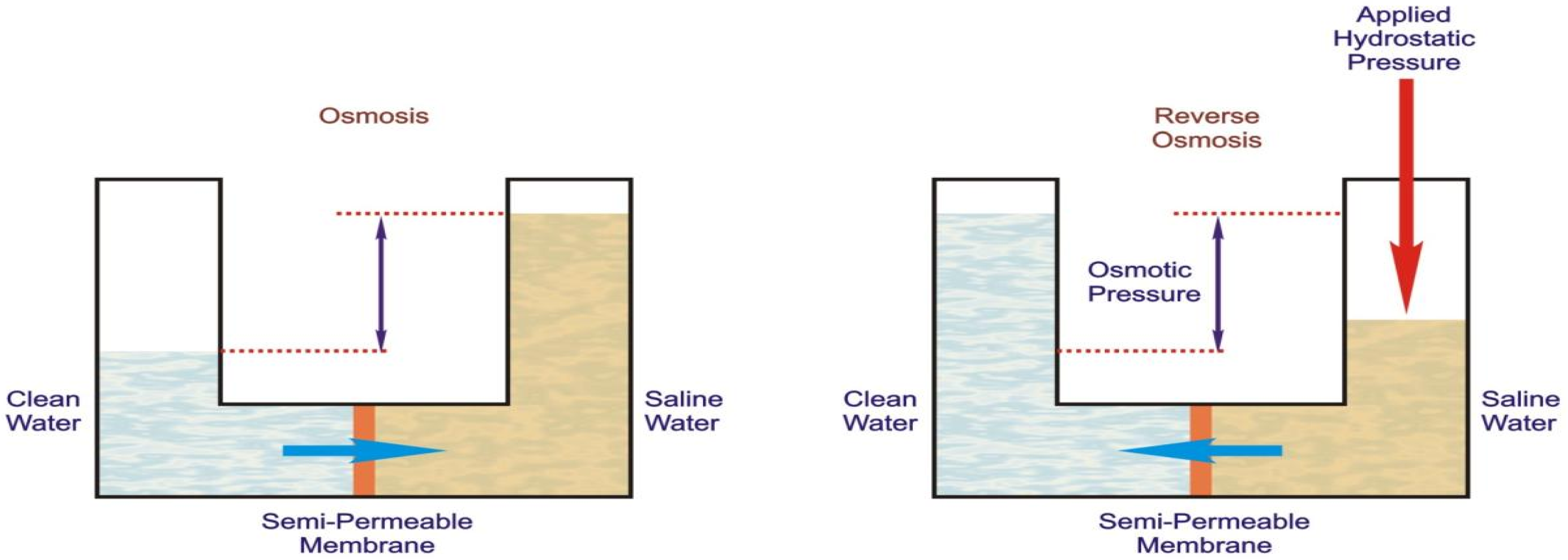
– Osmotic pressure describes the tendency for solute to diffuse from higher concentration region to lower concentration region until the entire solution reaches a homogenous concentration. If salt transport is stopped by membranes, a barrier that posses water "conductivity", instead of having salt passing through the membranes, water from the lower salinity region will diffuse through the barrier until TDS level in both chambers are equal.





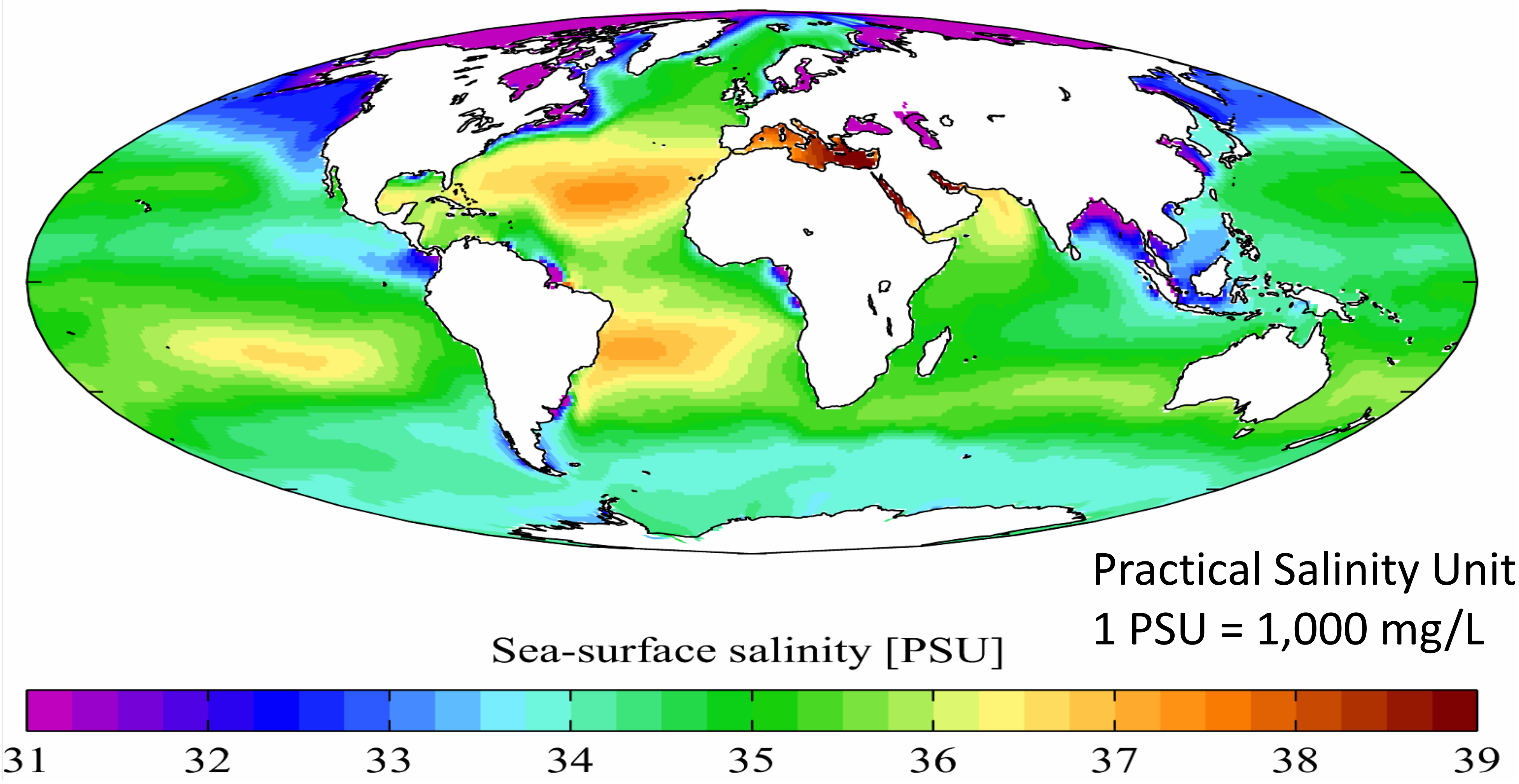
Reverse Osmosis: The Basic Principle

- To force water flow from high TDS solution across the membrane where TDS is much lower on the other side, hydraulic pressure will be needed.



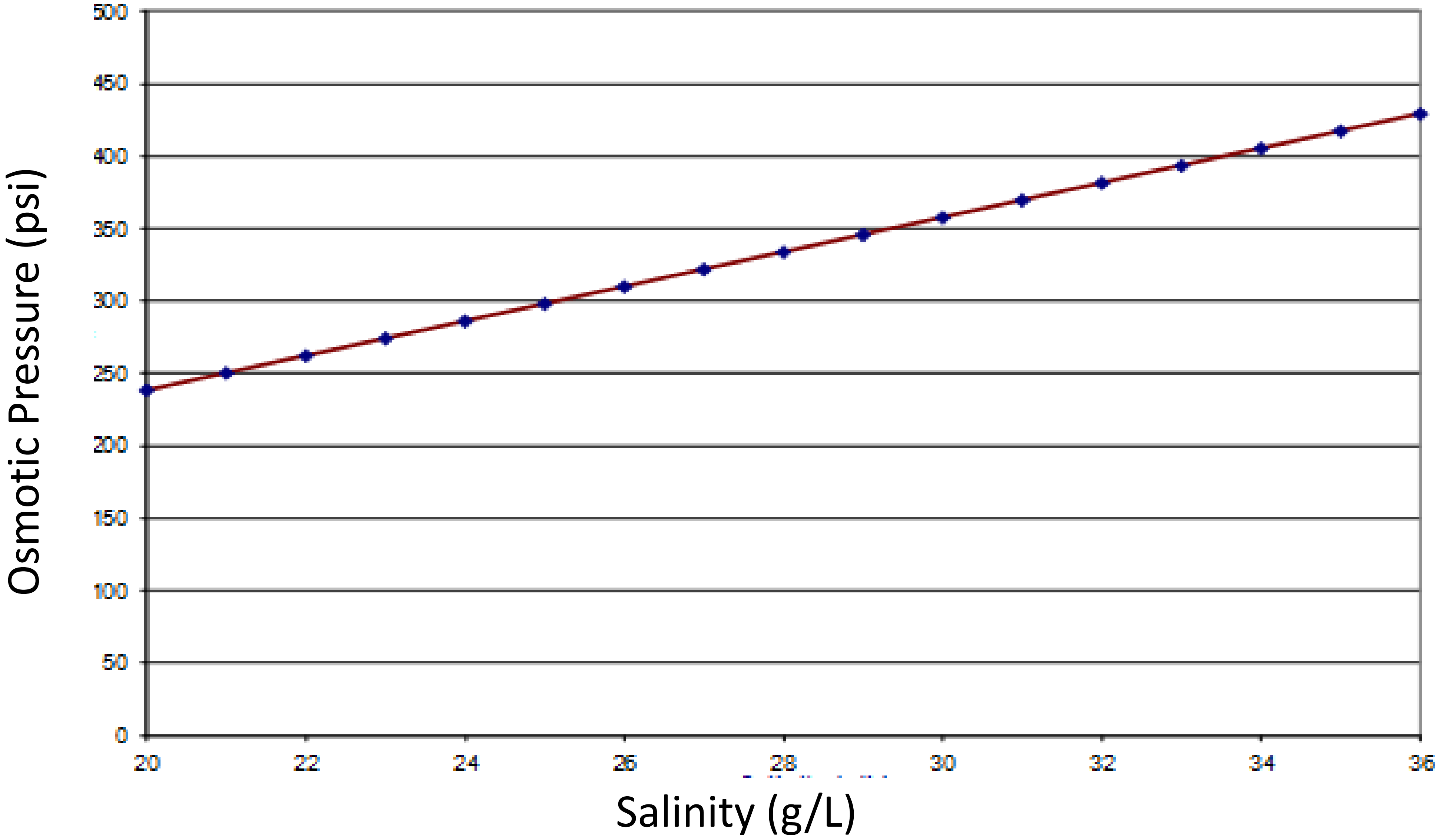
Global Seawater Salinity

– Ranges from 31,000 – 39,000 mg/L; with 35,000 mg/L as typical for desalination

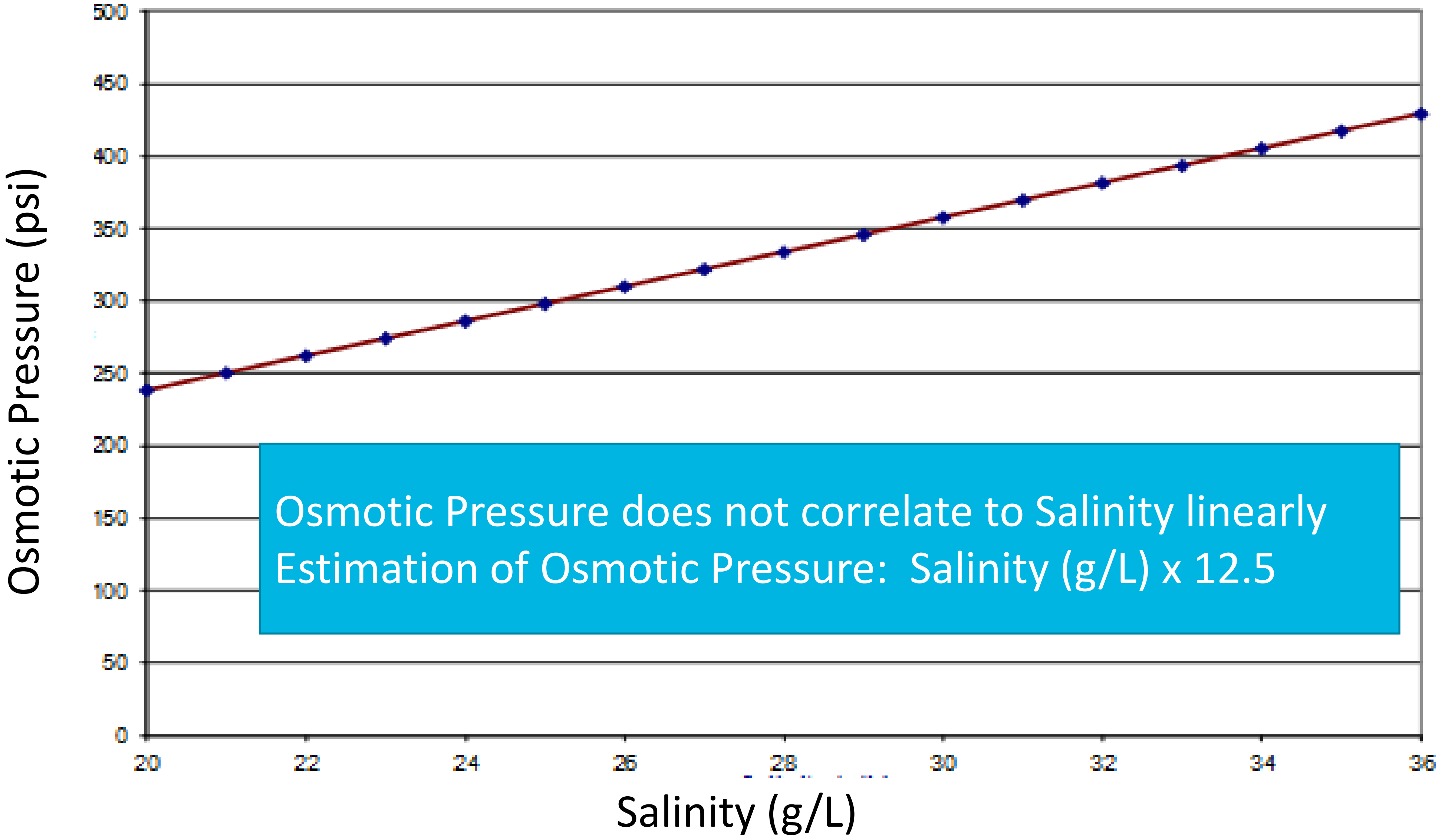


Practical Salinity Unit
1 PSU = 1,000 mg/L

Osmotic Pressure at 20 ºC



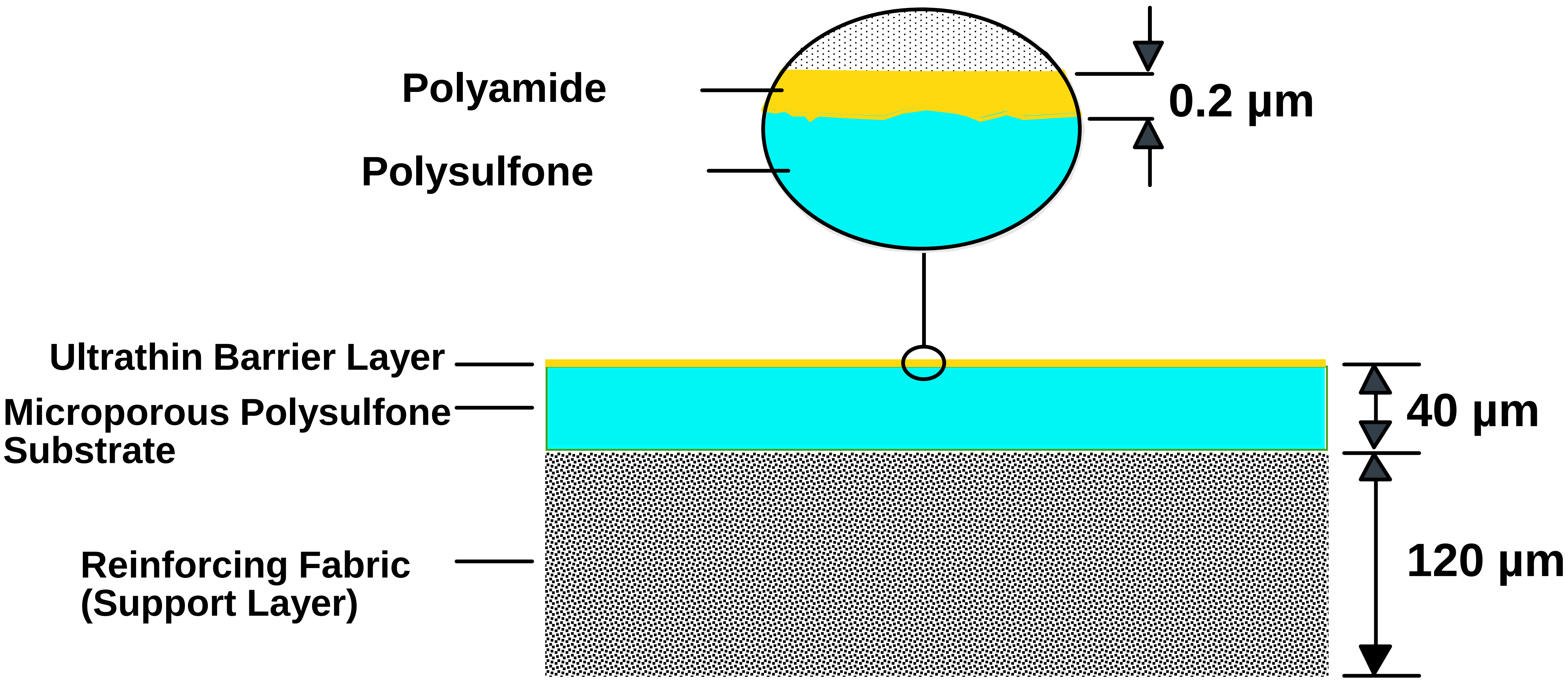
Equation for Salinity vs. Osmotic Pressure



Pressure Required for Seawater Desalination

- Theoretical Minimum Energy: 1.02 kWh/m^3
  - Consider osmotic pressure only
- Practical Minimum Energy: 1.52 kWh/m^3
  - Assuming all pumps, valves, piping head-loss, Energy Recovery Devices all work perfectly
- Best Operated SWRO Plant: 2 – 2.5 kWh/m^3

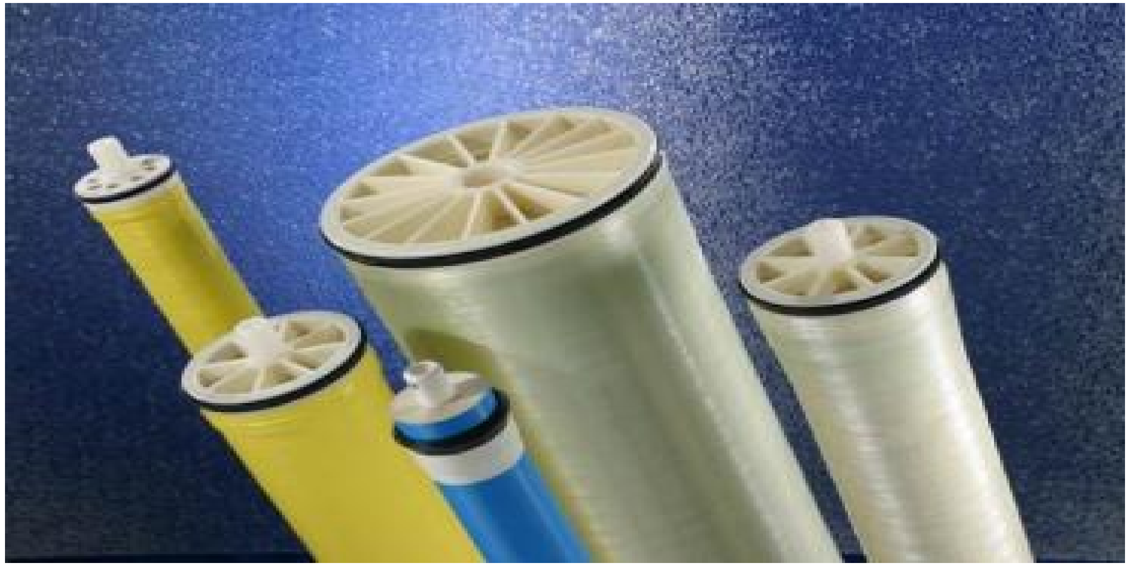
Schematic Cross-Section of Thin-film Composite RO Membranes



Types of Desalination Membranes

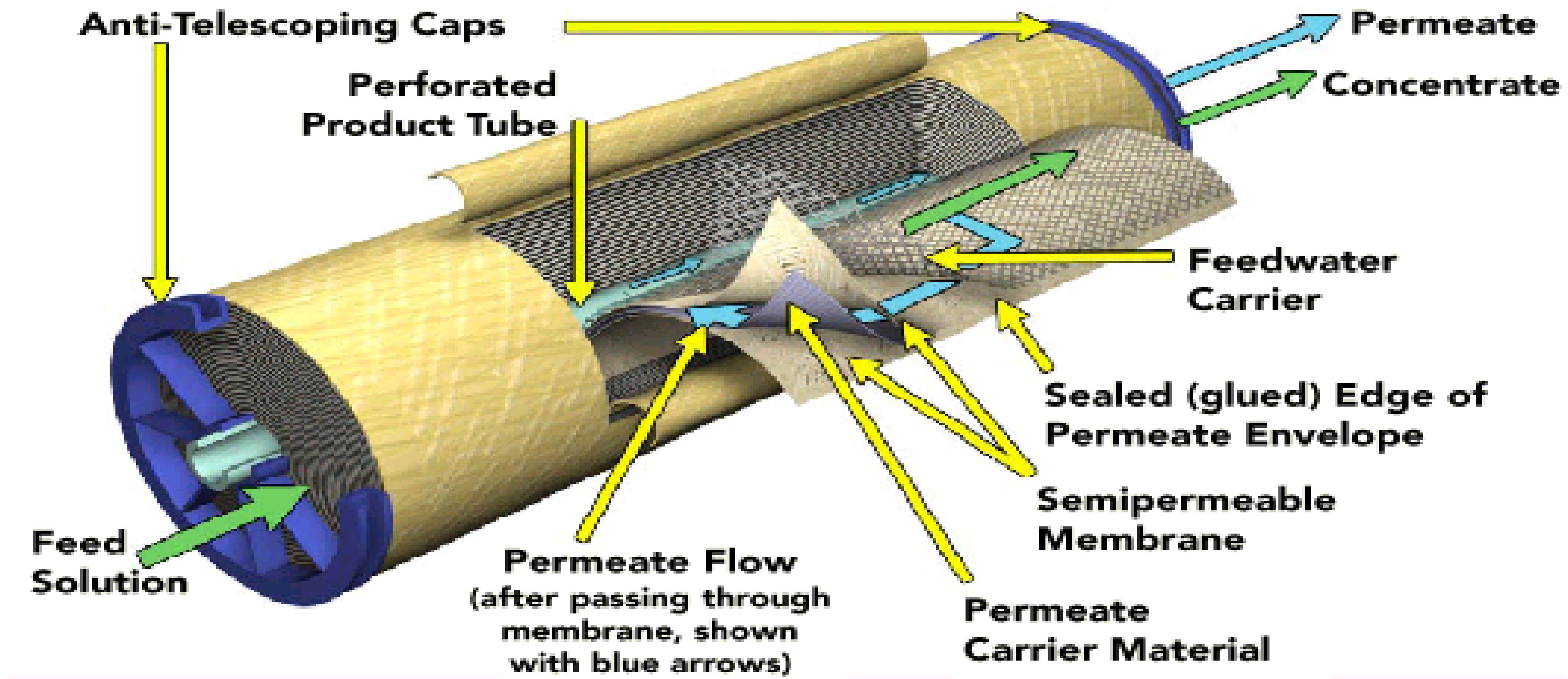
- Nanofiltration (NF) 50 - 225 psi
  - Good for lower TDS, groundwater (with double-valence ions) desalination, or NOM removal applications
  - Rejection % for single valent ions not as good as RO, but still > 95%
- Reverse Osmosis

Brackish water	150 - 600 psi
Seawater	800 - 1000 psi

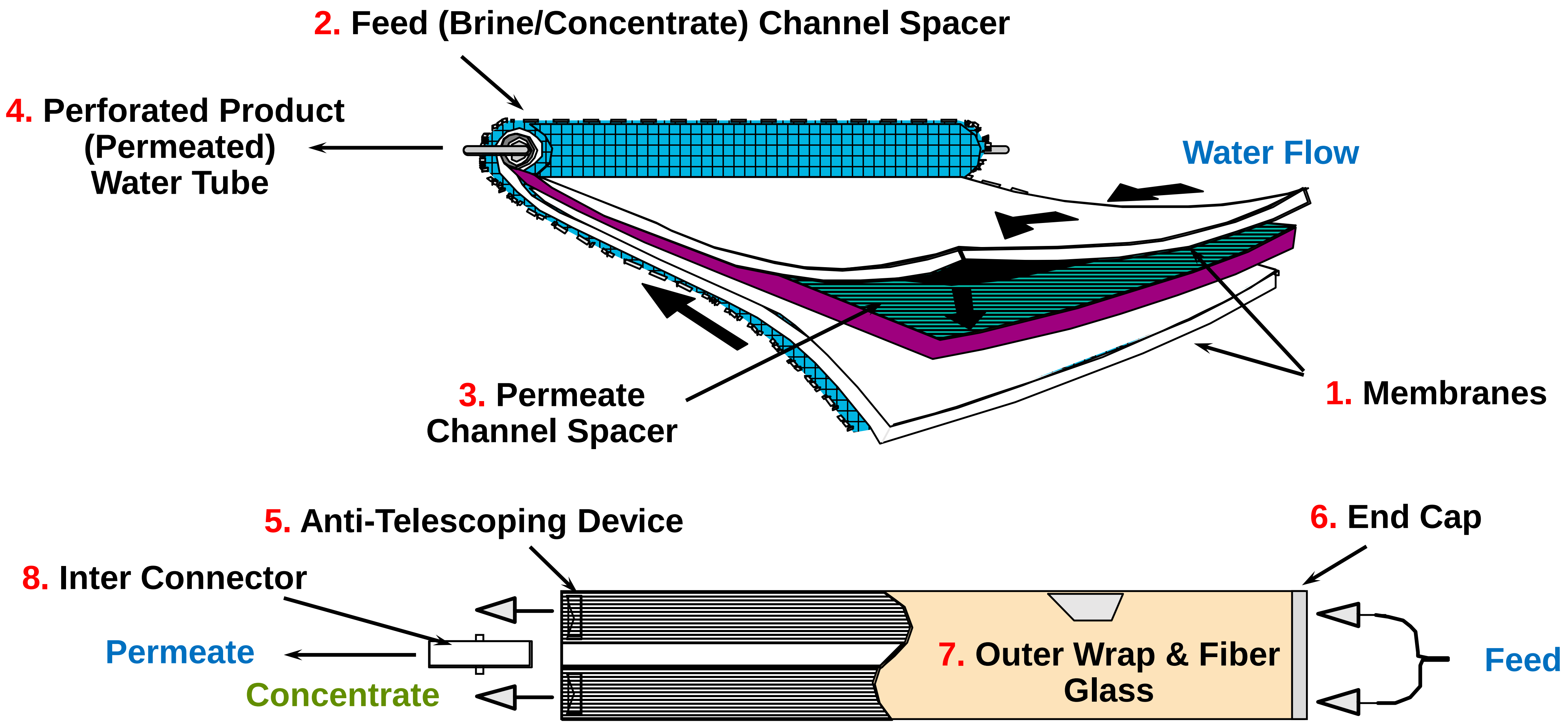


Construction of RO Element, Skid & System

Membrane element Arrangement

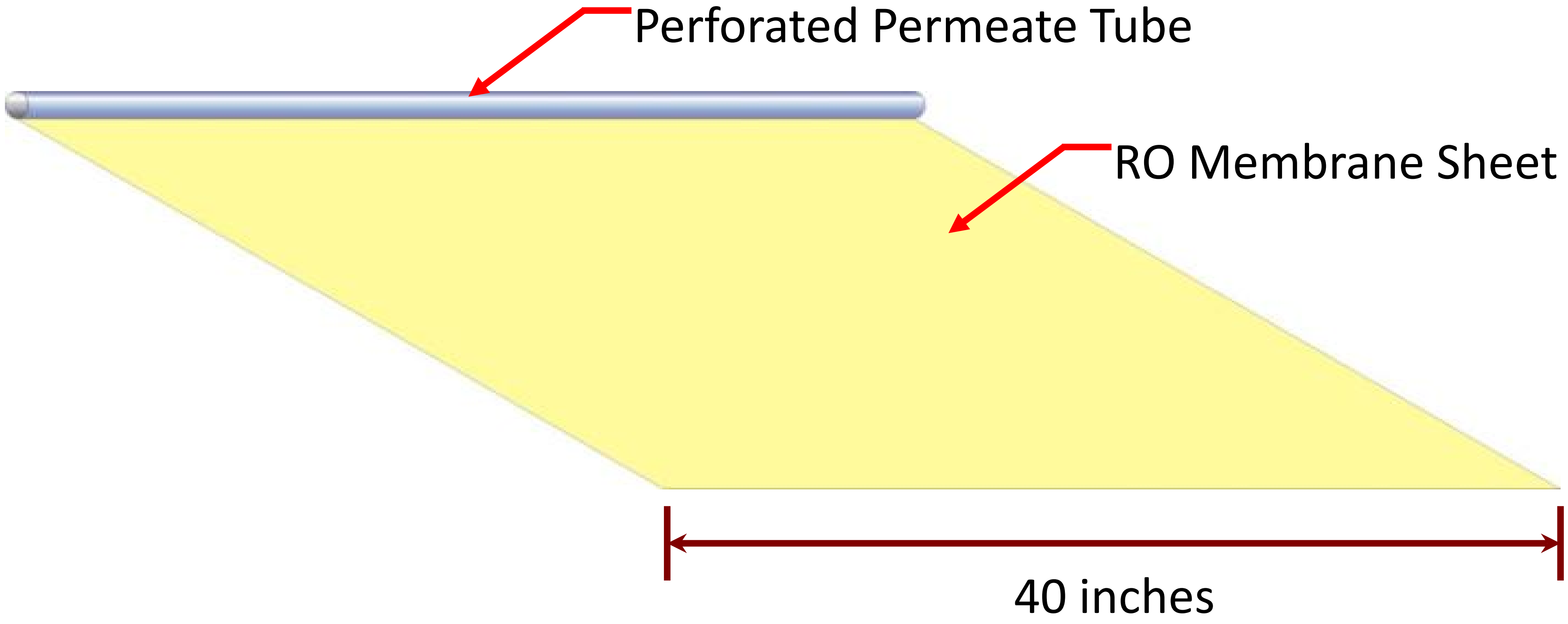


Spiral Wound Element



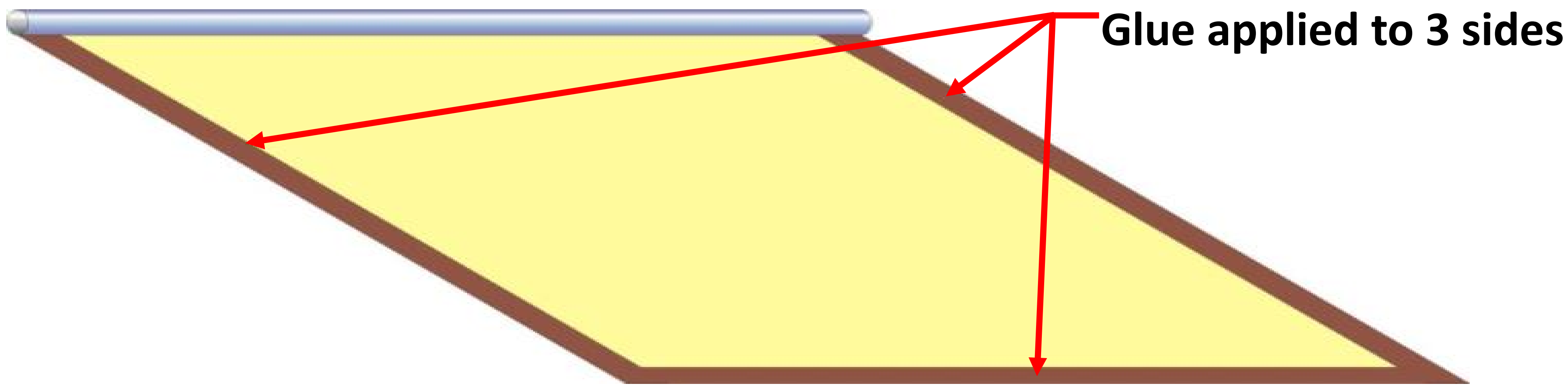
Manufacture of a Spiral Wound Element

- Step 1



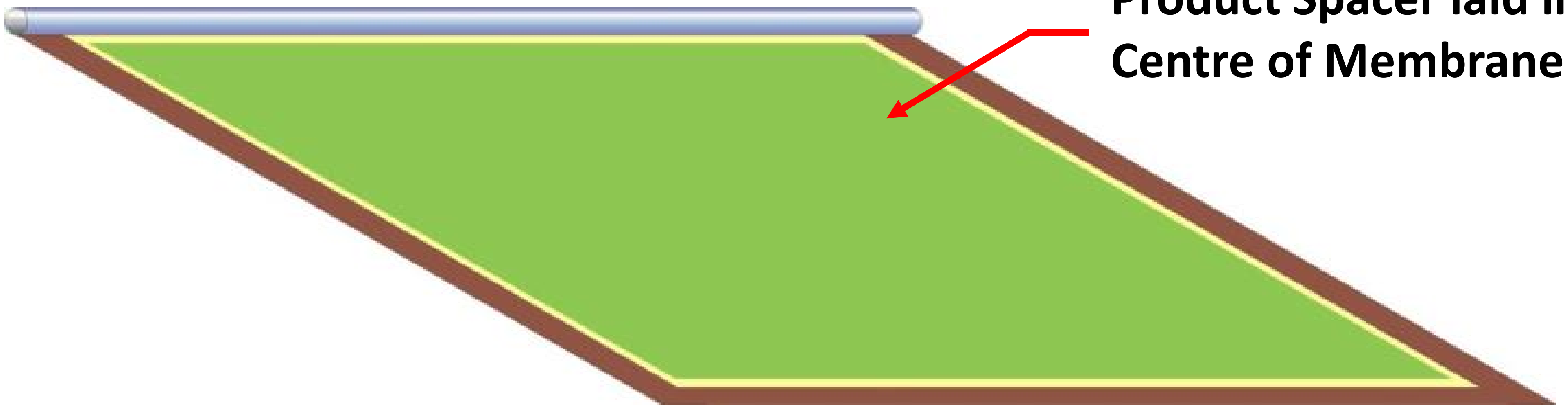
Manufacture of a Spiral Wound Element

- Step 2



Manufacture of a Spiral Wound Element

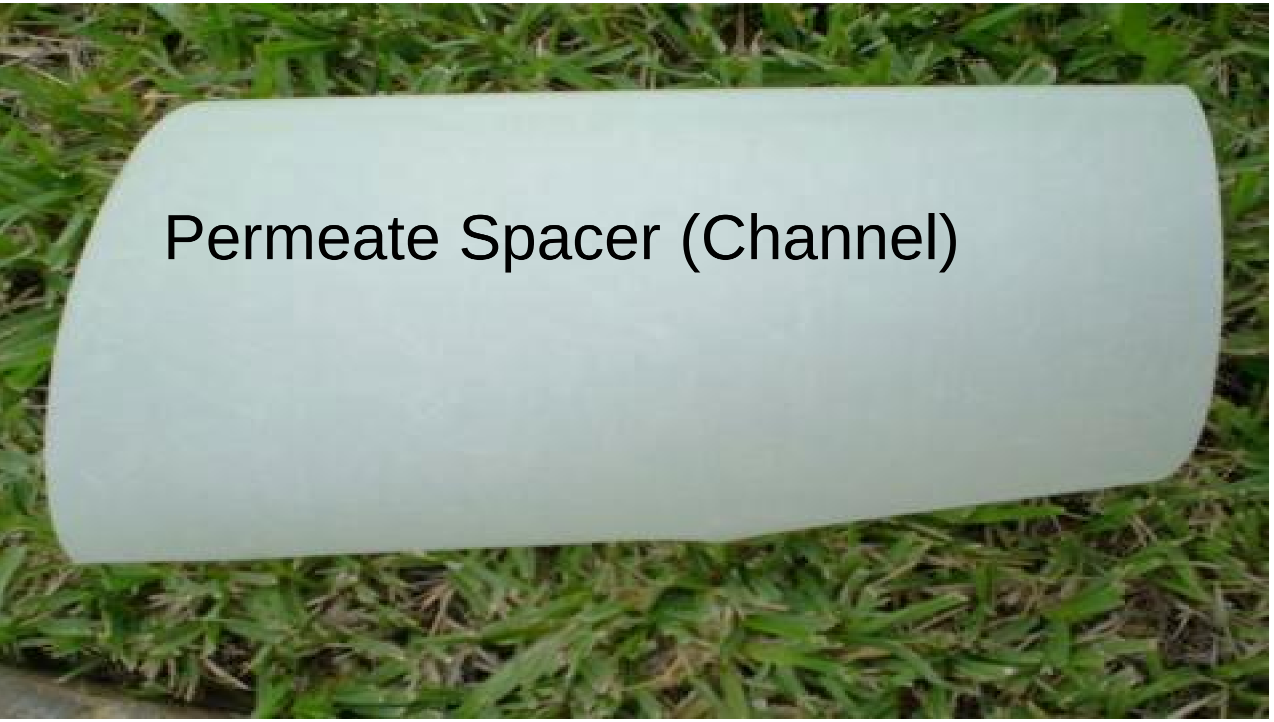
- Step 3



Product Spacer laid in Centre of Membrane Sheet

Feed Channel and Permeate Channel

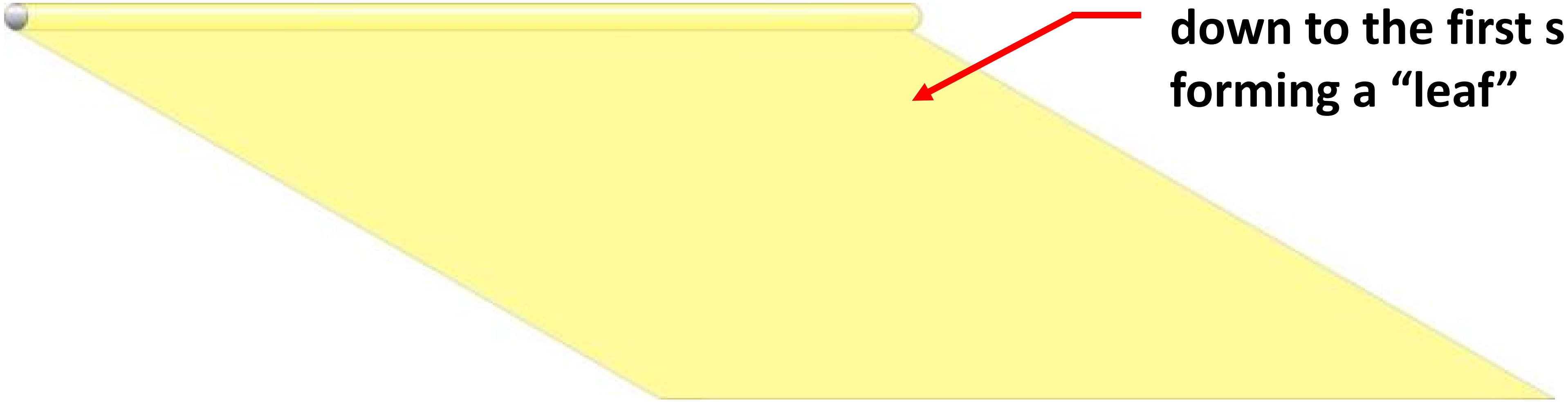
Feed Spacer (Channel)



Spacer: To provide space for water to flow across membrane surface

Manufacture of a Spiral Wound Element

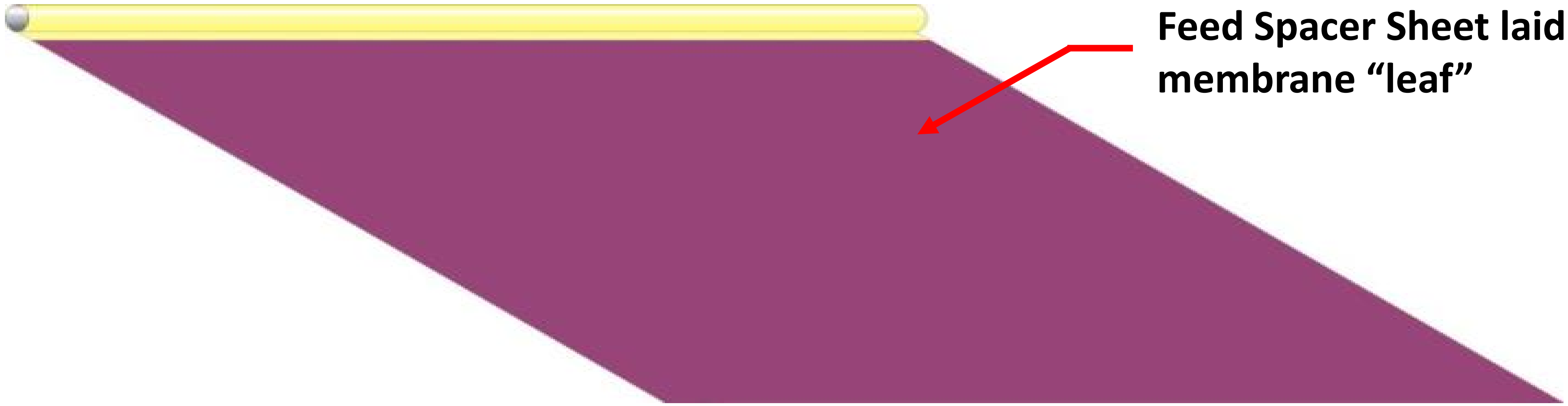
– Step 4



Second Membrane Sheet glued down to the first sheet, forming a "leaf"

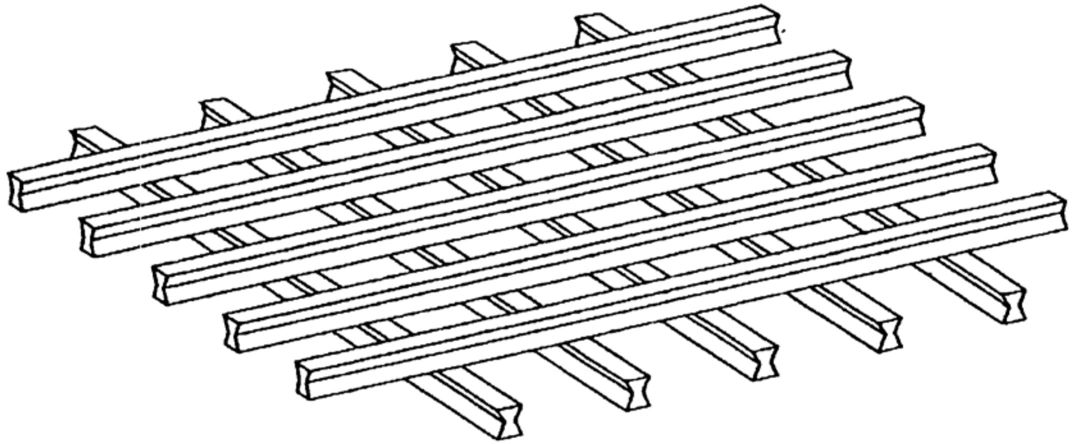
Manufacture of a Spiral Wound Element

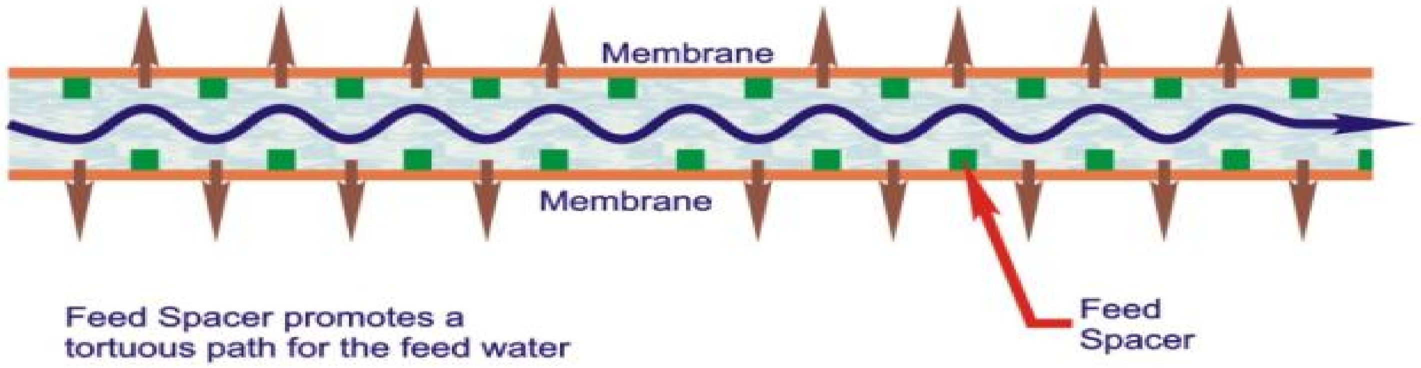
– Step 5



Feed Spacer Sheet laid on top of membrane “leaf”

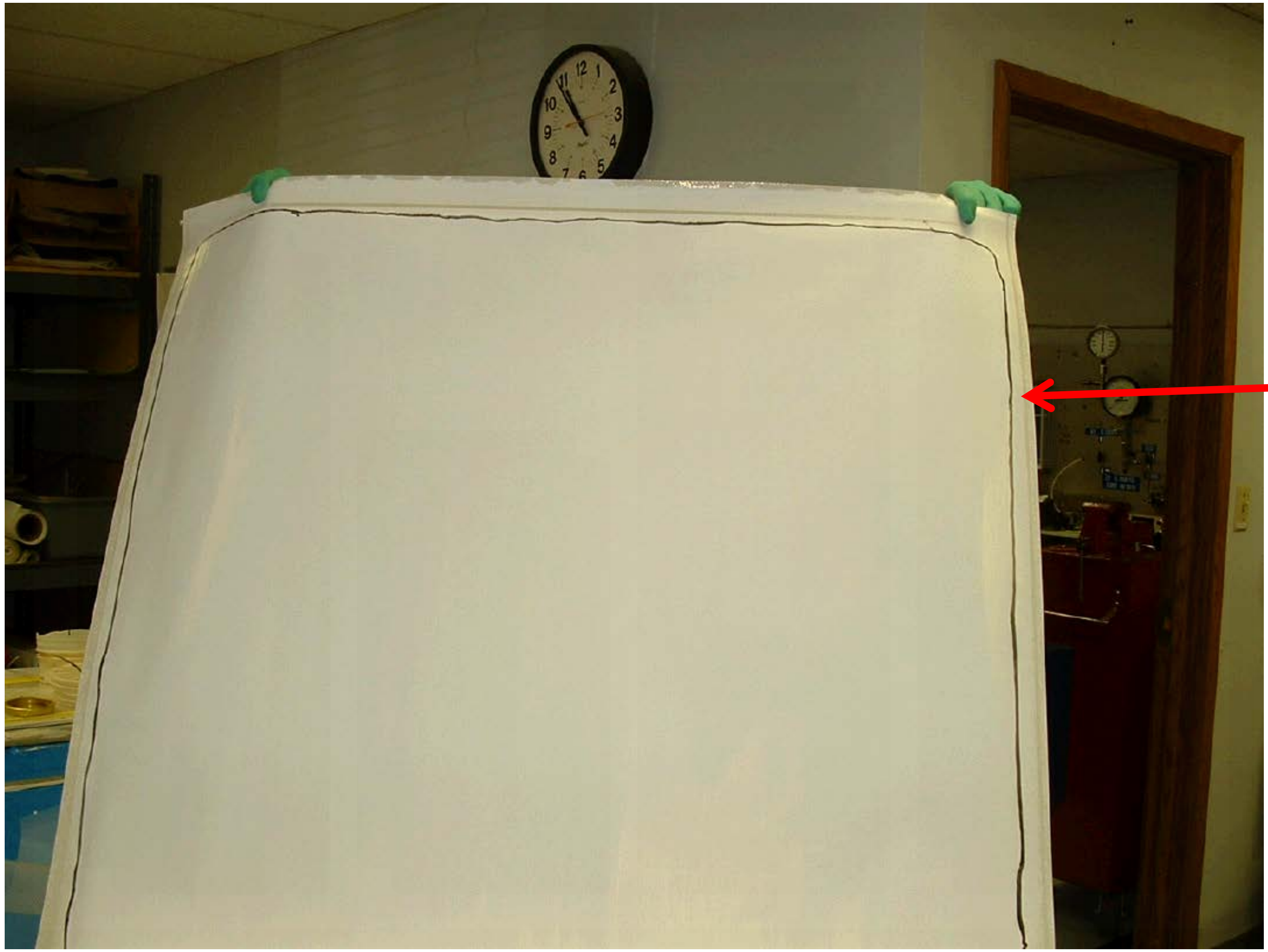
Typical Feed Spacer Detail





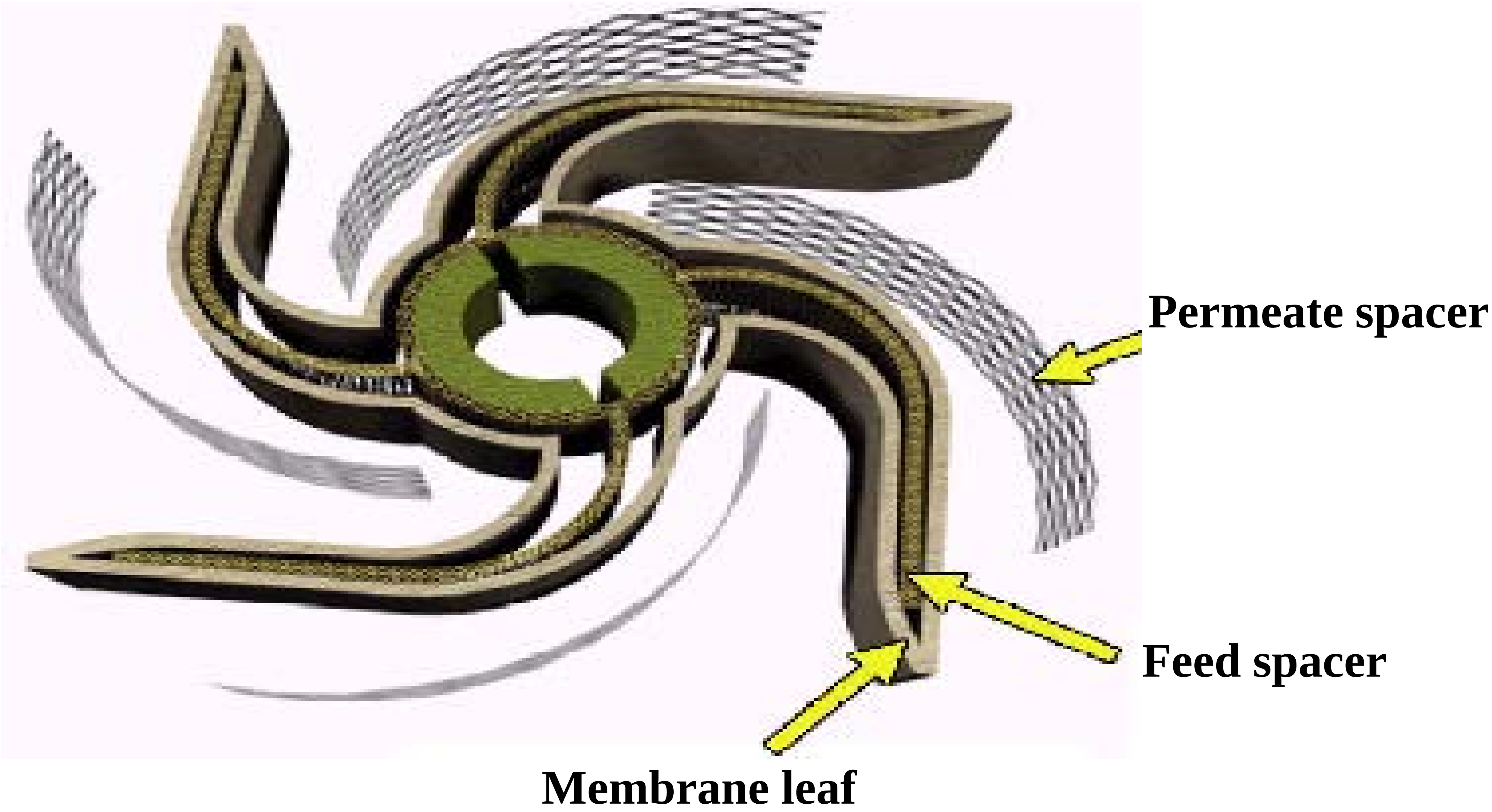
- Typical feed spacer 0.65 - 0.85 mm thick
- Promotes tortuous flow path for feed
- Solids can easily plug the feed spacer channels
- Thicker spacer (0.8 – 0.85 mm) used for higher fouling sources

Water entering the envelope is trapped; it can only go to the product water tube



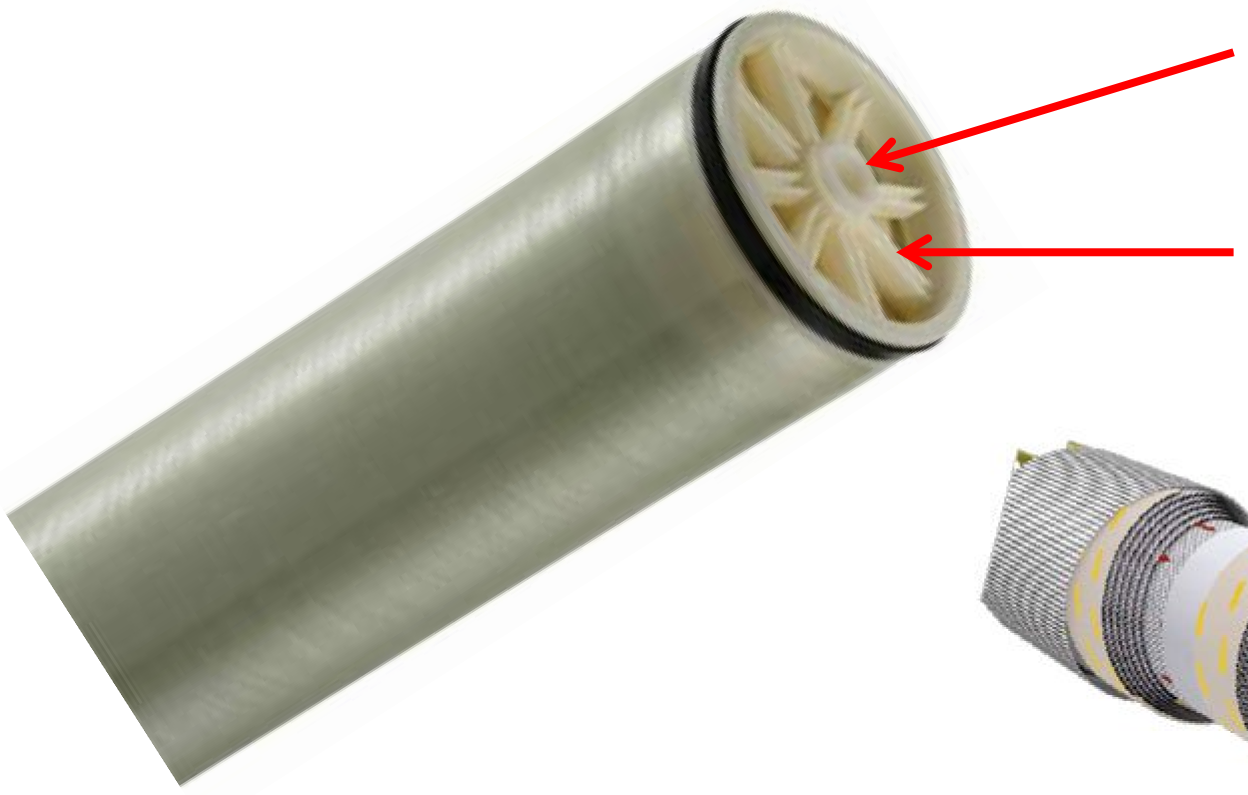
Glue Line

Illustration of RO Membrane Construction



Product Water Tube

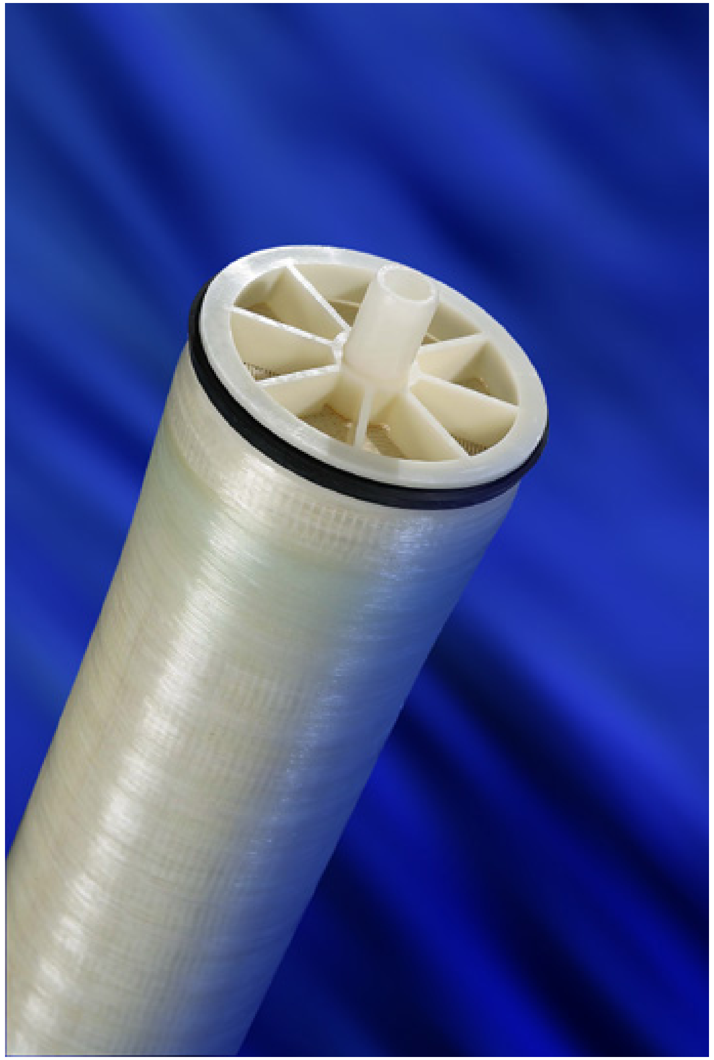
– Serves as center support and collects permeate from permeate carrier



Damaged RO Element

- Excessive Fouling
- Telescoping

Tape it and Fiberglass it



Boxed

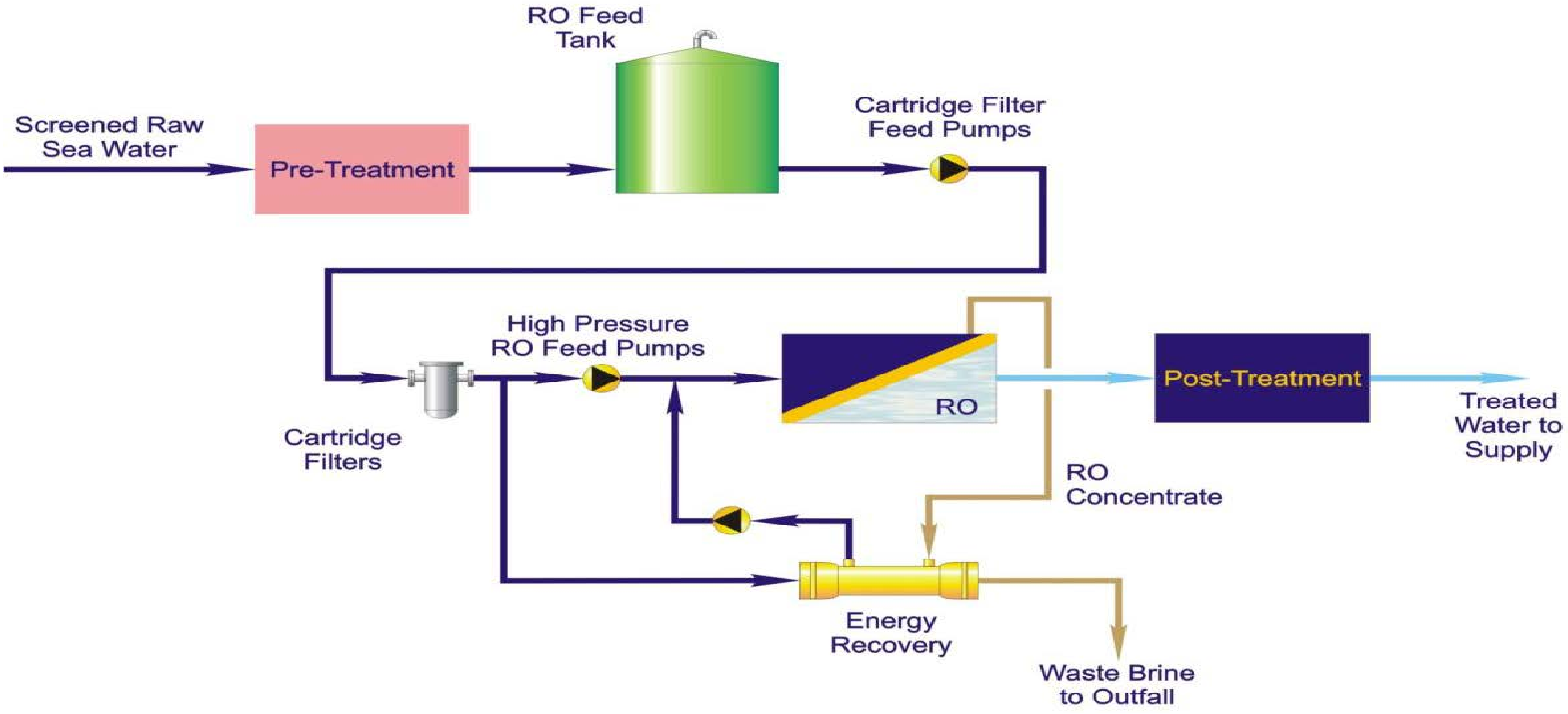
Bagged

Unwrapped Upon Arrival at the Plant…

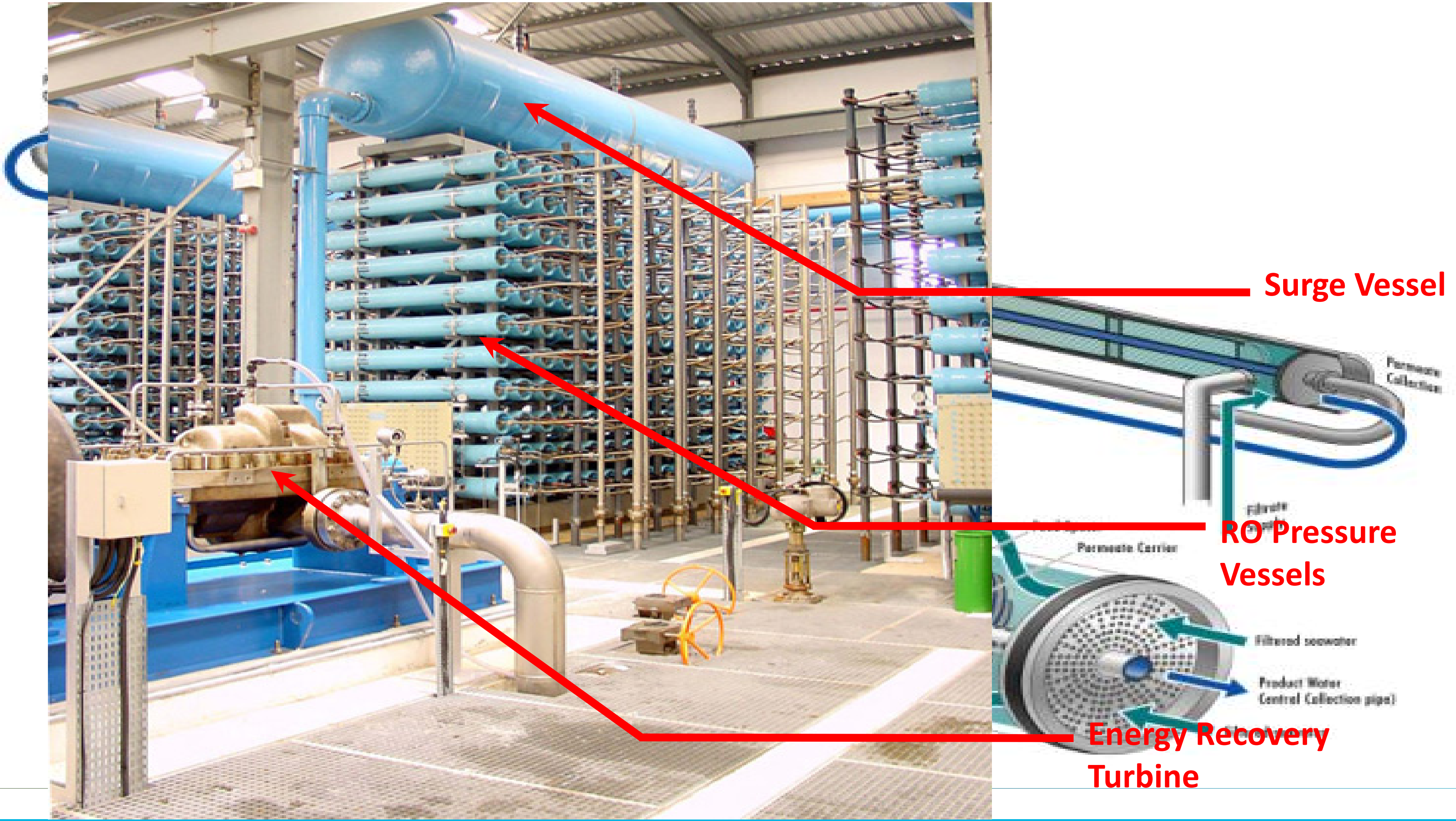
Loaded …

RO Skids & Plants

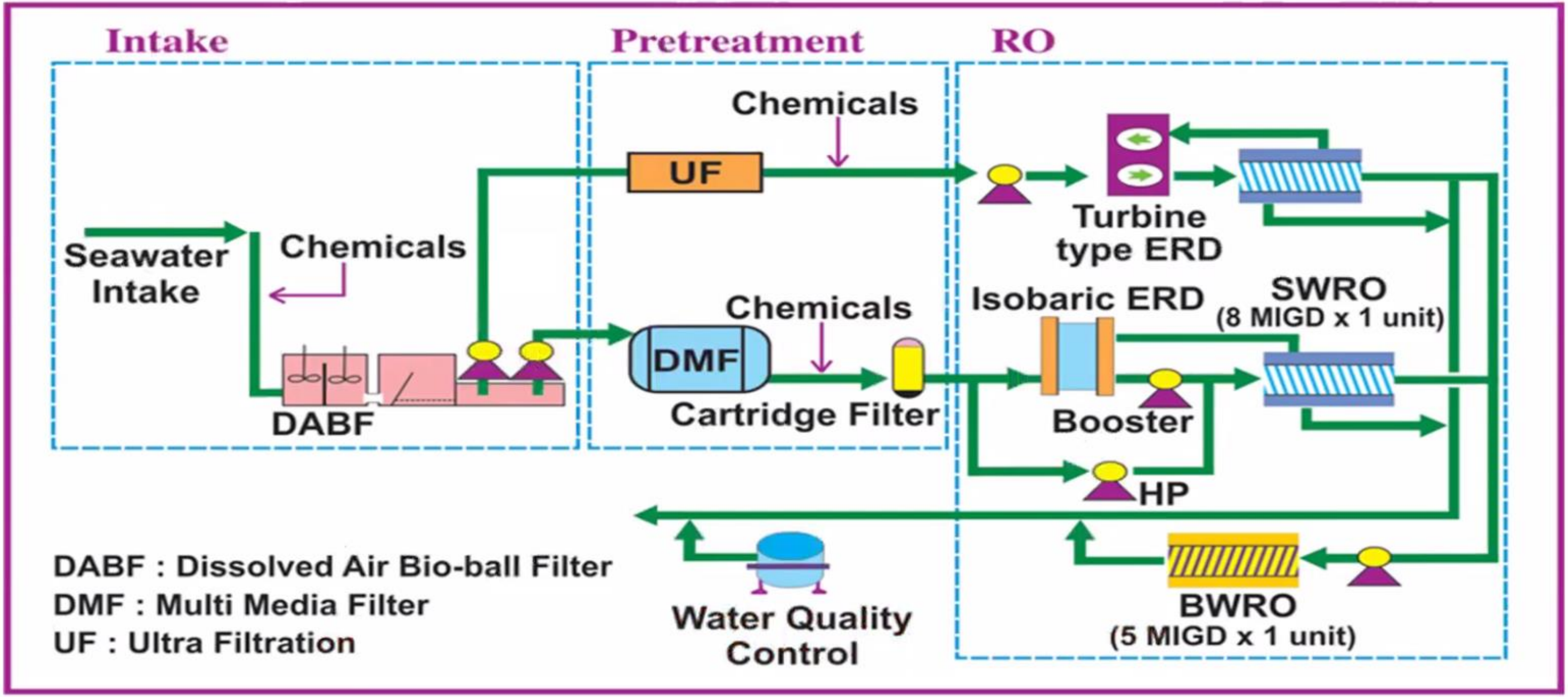
Typical PFD for Seawater Reverse Osmosis (SWRO)



Seawater Reverse Osmosis (SWRO)



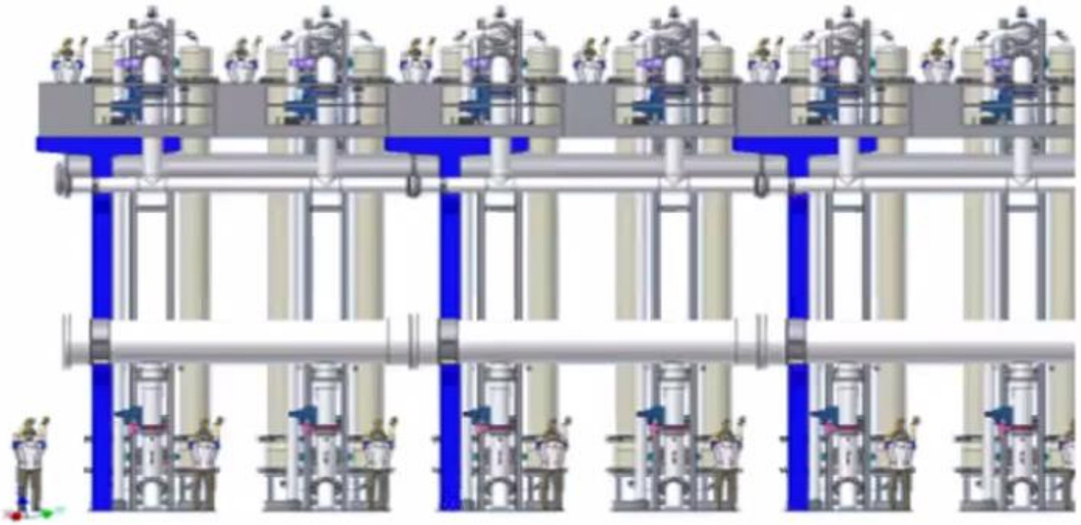
Typical RO Treatment Processes



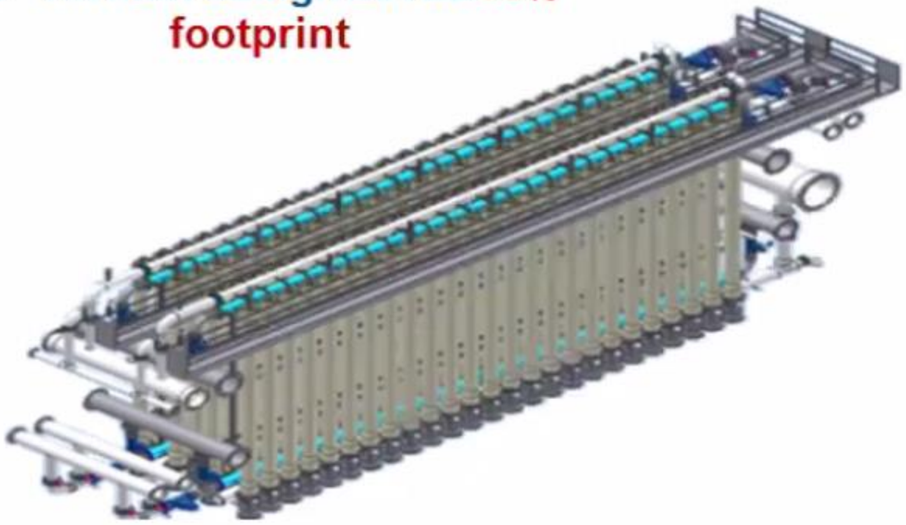
Advancements in SWRO: New RO Membranes & Modules

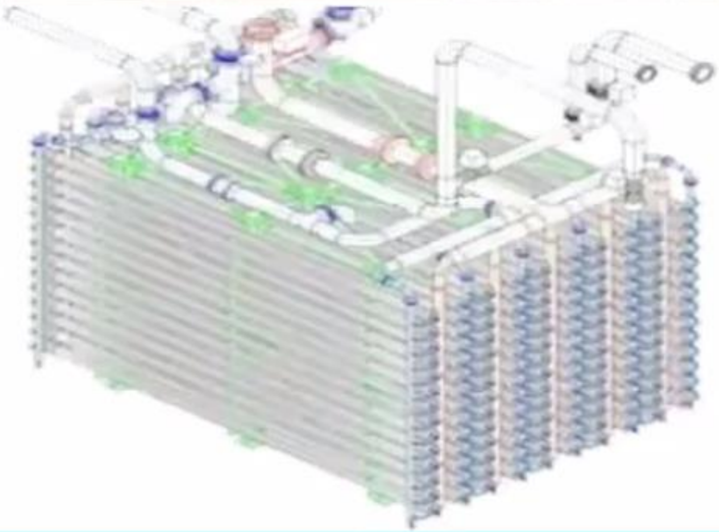
- LPRO & ULPRO Membranes
  - ~80 – 200 psi for Brackish Water
  - 600 – 900 psi for Seawater
- 16” Diameter RO Membrane Elements
  - Lower Capital Costs (One 16” element = 5.5 standard elements)
  - Smaller Equipment Footprint
  - Lower O&M Requirements

Advancements in SWRO: 16” Vertical Membranes, Sorek



16” vertical design saves **30%** footprint



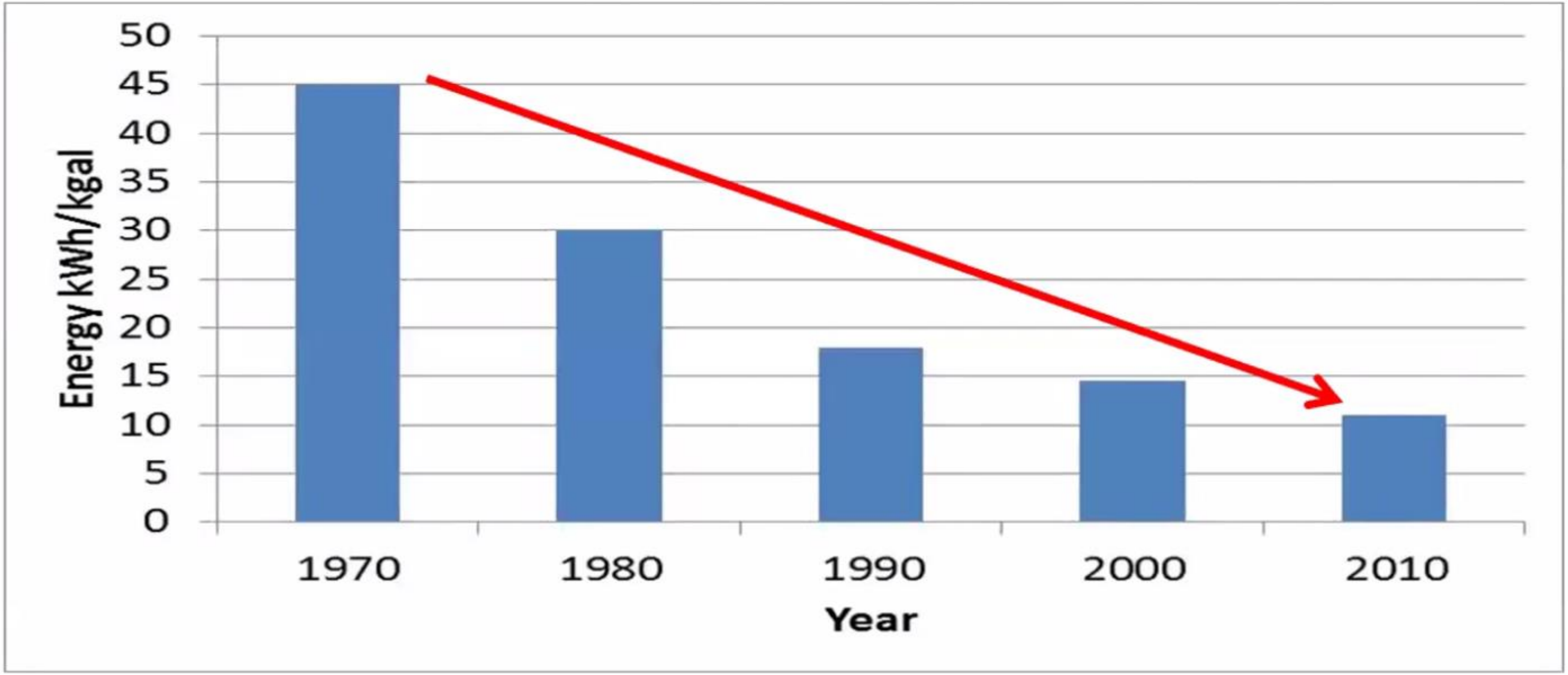


Standard 8” Horizontal design

Water/Energy Nexus: Energy Optimization

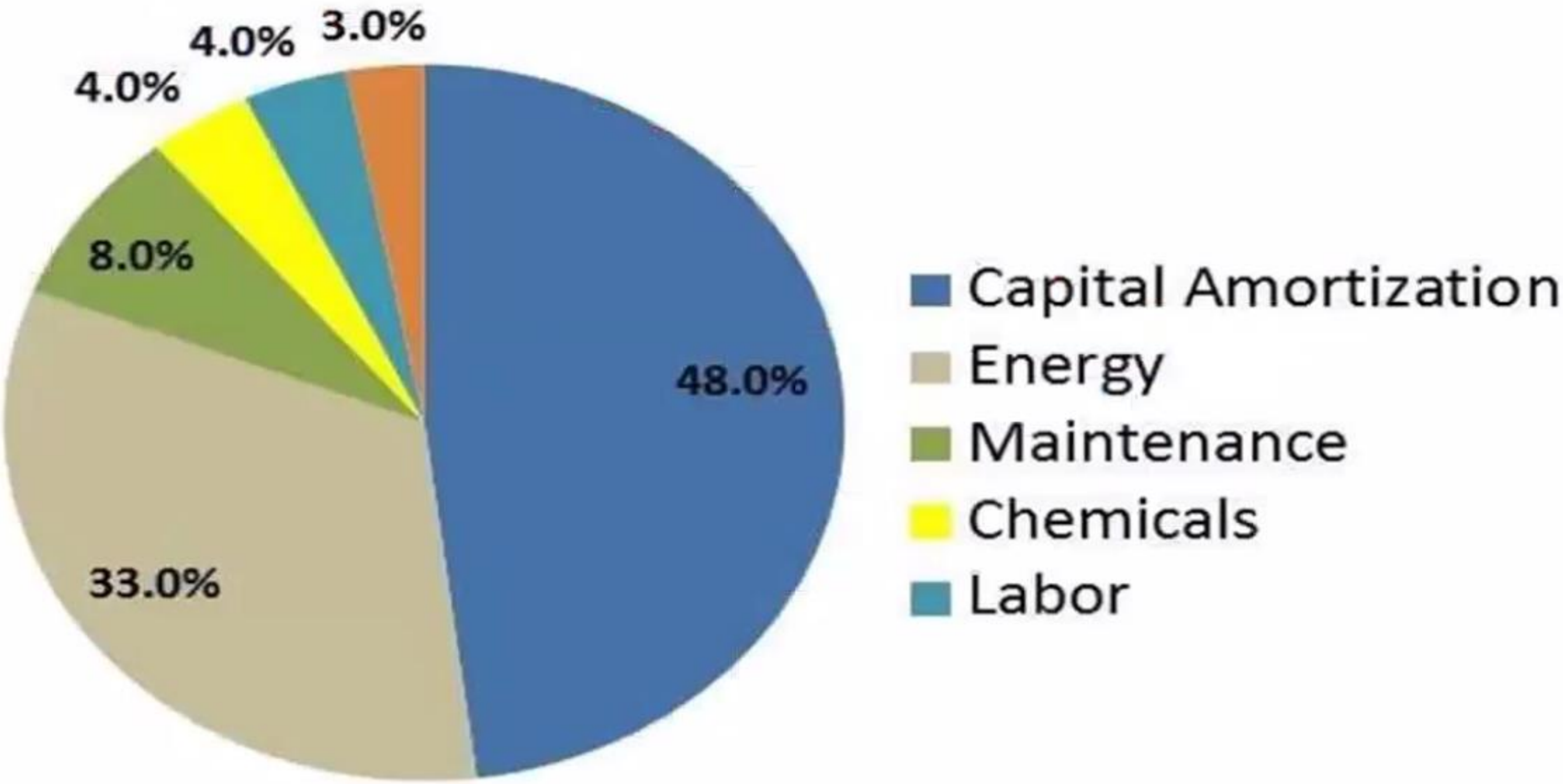
Minimizing Energy Consumption & Taping into Renewable Energy

Historical Energy Consumption of Seawater Desalination



SWRO Cost Breakdown

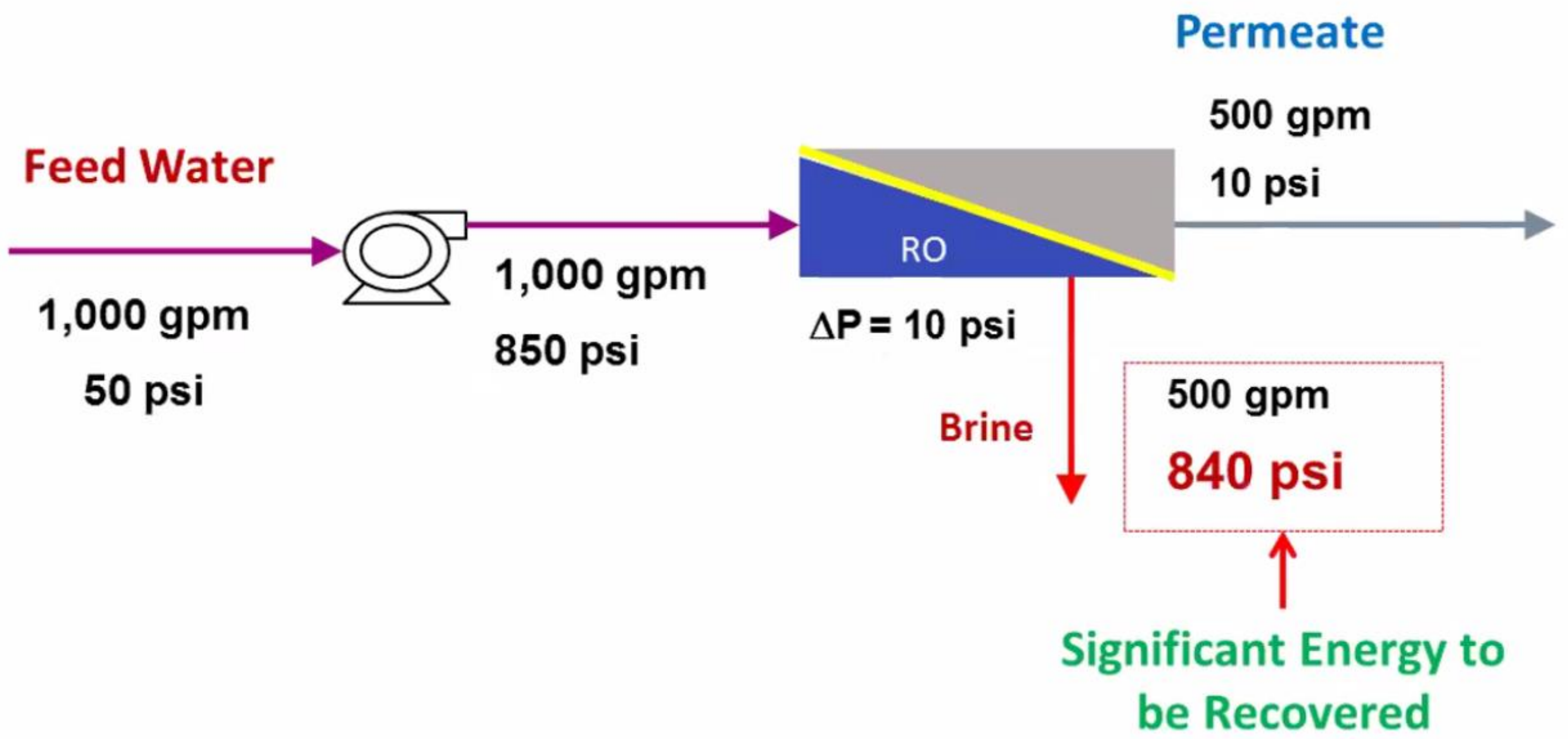
- Capital & Energy cost comprises > 80% of project cost



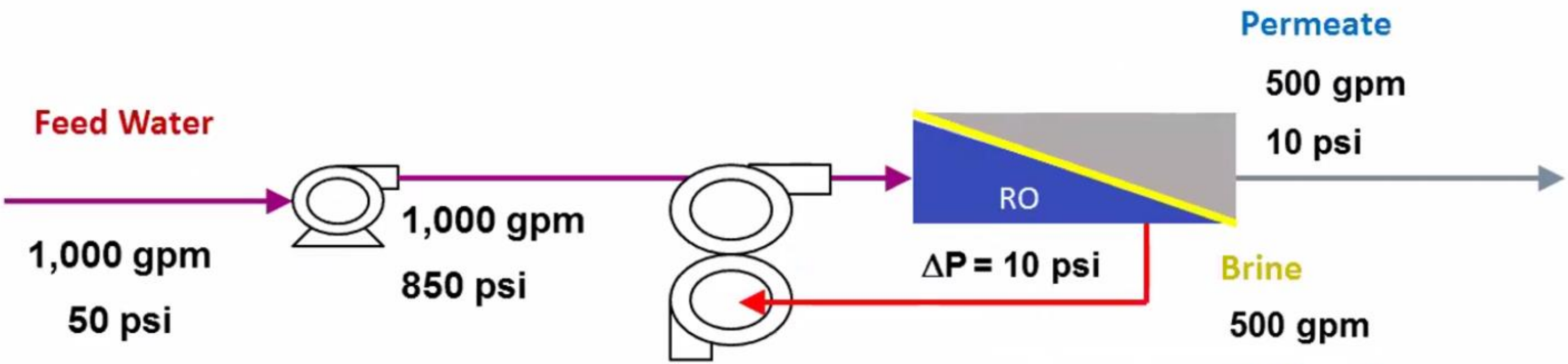
Factors Contributing to Lower RO Energy Consumption

- Better RO Membranes (Higher Permeability)
- High Efficiency Pumps
- High Efficiency Motors
- VFD (Variable frequency drive)
- Energy Recovery Devices (ERD)

Energy Recovery from RO Brine



Turbocharger: Mechanical Energy Recovery Device

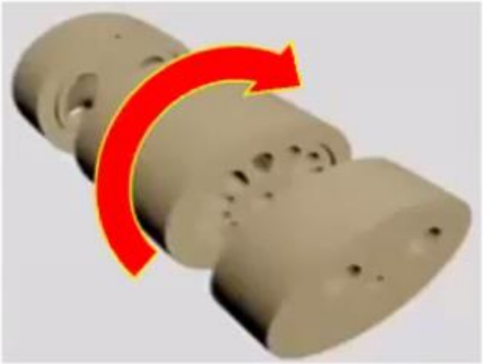


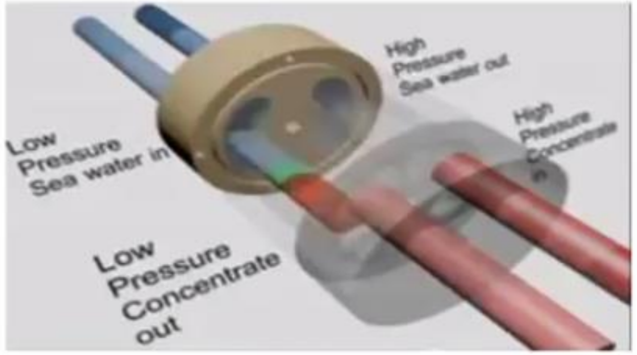
Hydraulic → Mechanical → Hydraulic

Energy Recovery Efficiency ~ 80%

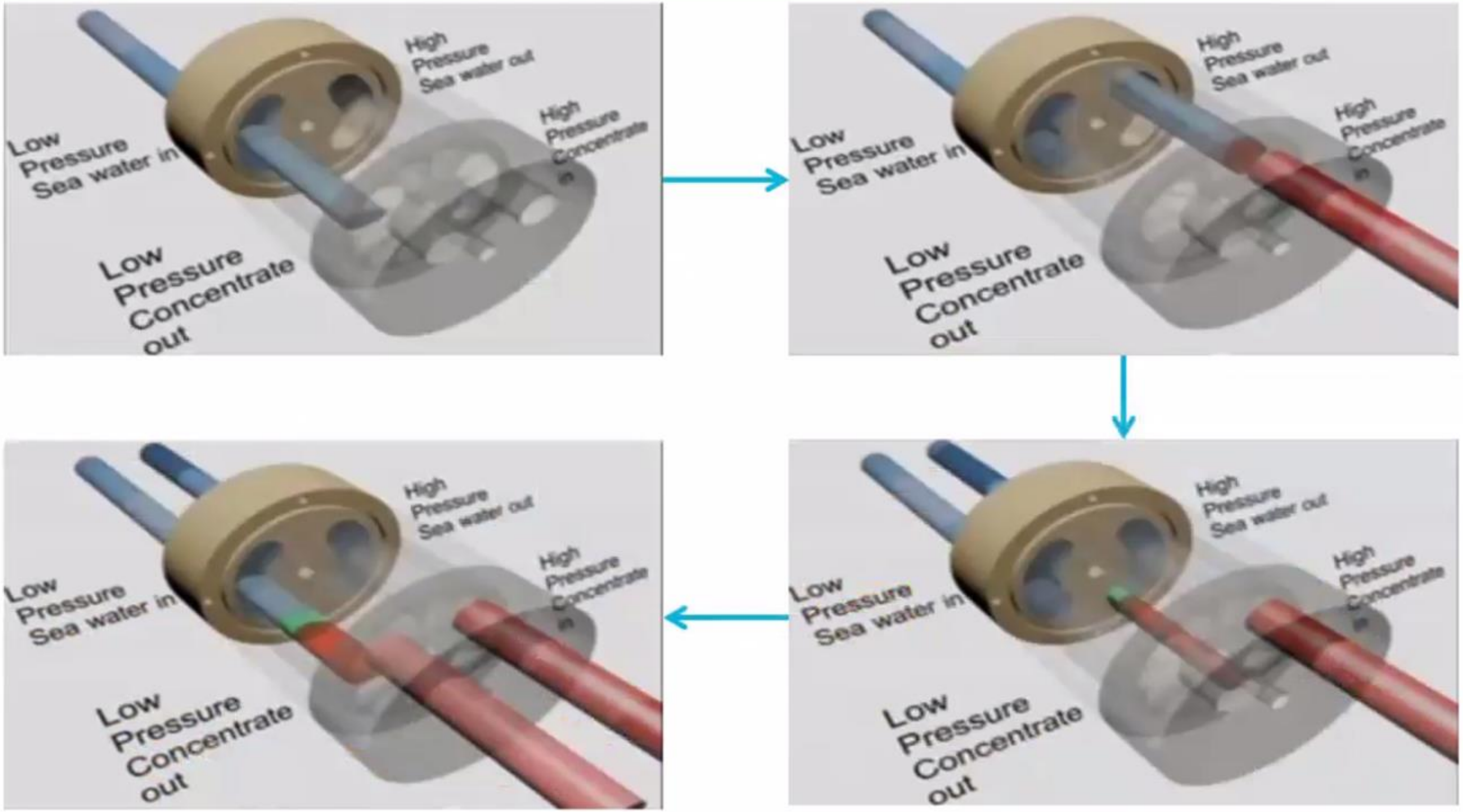
High Efficiency Energy Recovery

- **Isobaric devices (95-99%)**
  - **Piston style (DWEER by Flowserve)**
  - **Rotary pressure exchangers (PX by ERI)**





Mechanism of ERI Isobaric ERD



Renewable Energy for Desalination

Solar PV

Wind

Ocean

Hydro

Solar Thermal

Biomass

Geothermal

Hydrogen

The Perth Plant (Australia)

- Wind-Powered Desalination Facility at Kwinana
  - 34.3 MGD (144 MLD) seawater desalination facility
  - 48 wind turbines (80 MW) generate more energy (270 GWh/yr) than the desalination plant needs (180 GWh/yr)
  - Connected to gas fired power grid to supplement in low-wind conditions, but “return” power over time

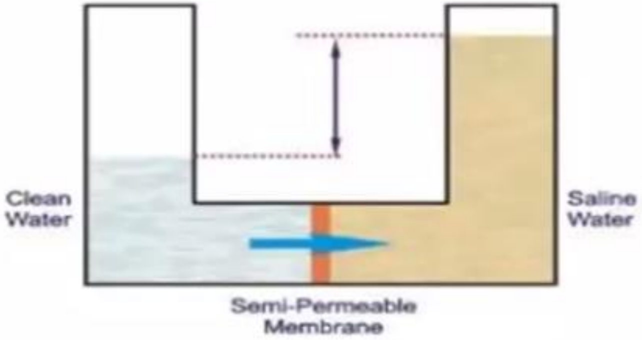
World's Largest EDR Plant (Barcelona)

- Treating surface water under wastewater influence
- 58 MGD (230 MLD; 2.54 m3/sec)
- 210 MW/day (29% for pretreatment; 71% for EDR)
- 3.6 MW Solar Farm

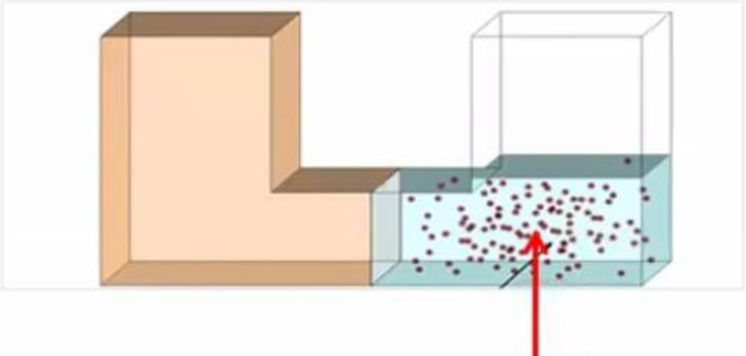
Emerging Desalination Technologies

Emerging Technology: Forward Osmosis

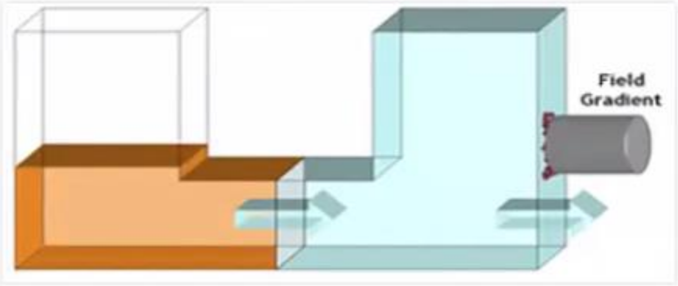
- Use osmotic agents in the Draw Solution
- No feed pressure required, Low Fouling
- FO membranes now available
- Can be used to treat VERY nasty and challenging water
- Draw agent recovery



Osmosis

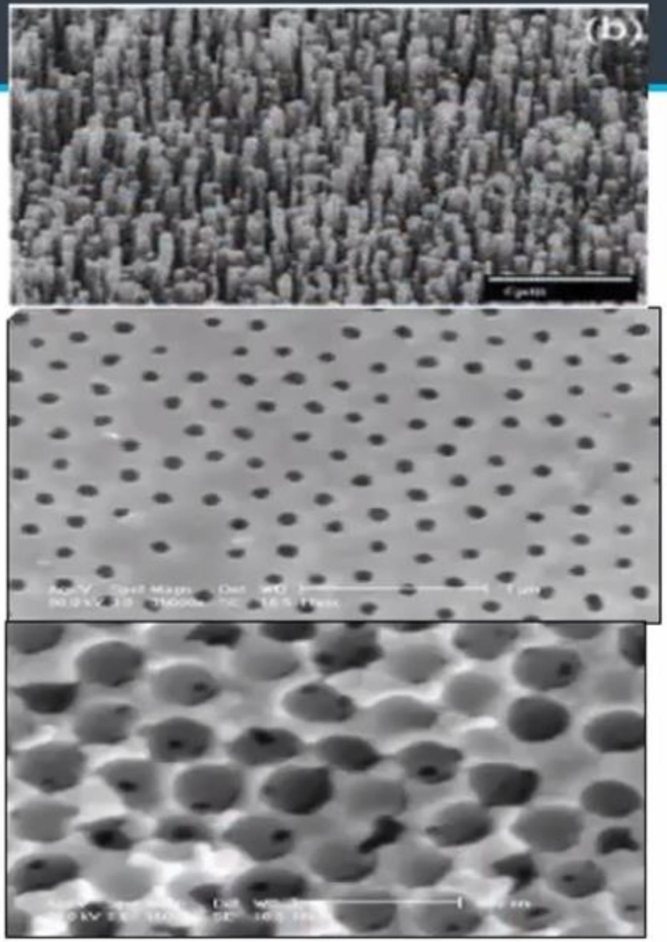


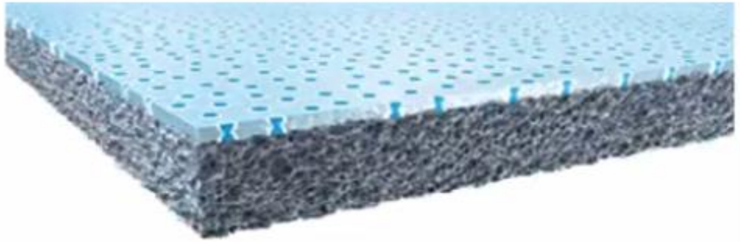
Draw Solution
(High Osmotic Pressure)



Emerging Technologies

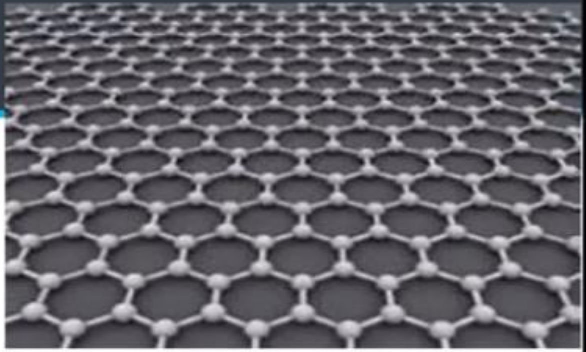
- Nano-Structured Membranes
  - Carbon Nanotubes
  - Inorganic/Organic Nanocomposites
- High Production (Flux) RO
  - Smooth membrane surface via surface modification
- Chlorine Resistance RO
  - Free Cl tolerance > 1 mg/L
- Biomimetic Membranes (Aquaporin)
- Membrane Distillation

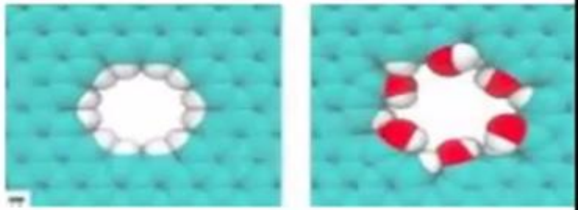


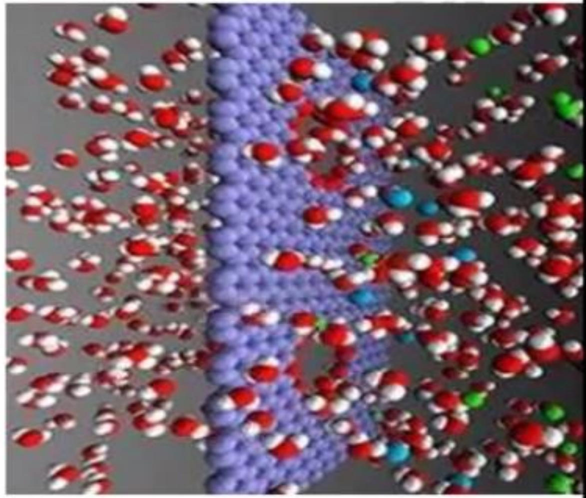


Graphene

- Nanoporous material (1.5 – 62 A^2)
- 1-atom thick of layered graphite
- Can "design" specific pore sizes
- Fast water convection, instead of slow diffusion
- Improve permeability by 100 -1,000 X
- Fouling resistant
- Chlorine tolerant
- Closer to mass production





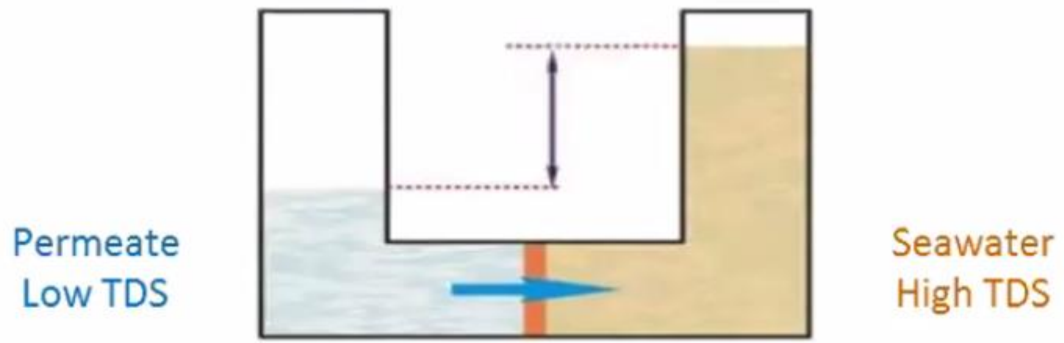


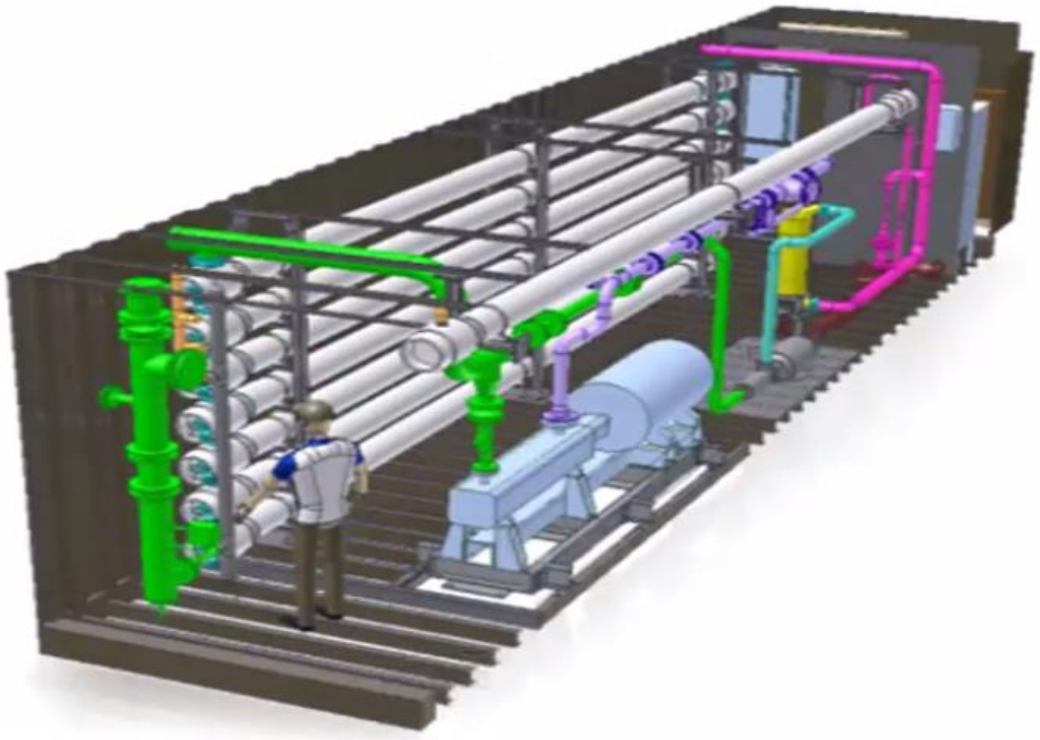
Innovative Chemical-Free Approach

- Utilizing biological filtration without coagulant addition
  - Control biological fouling by limiting AOC/BDOC
- Direct Osmosis Cleaning (DOC)

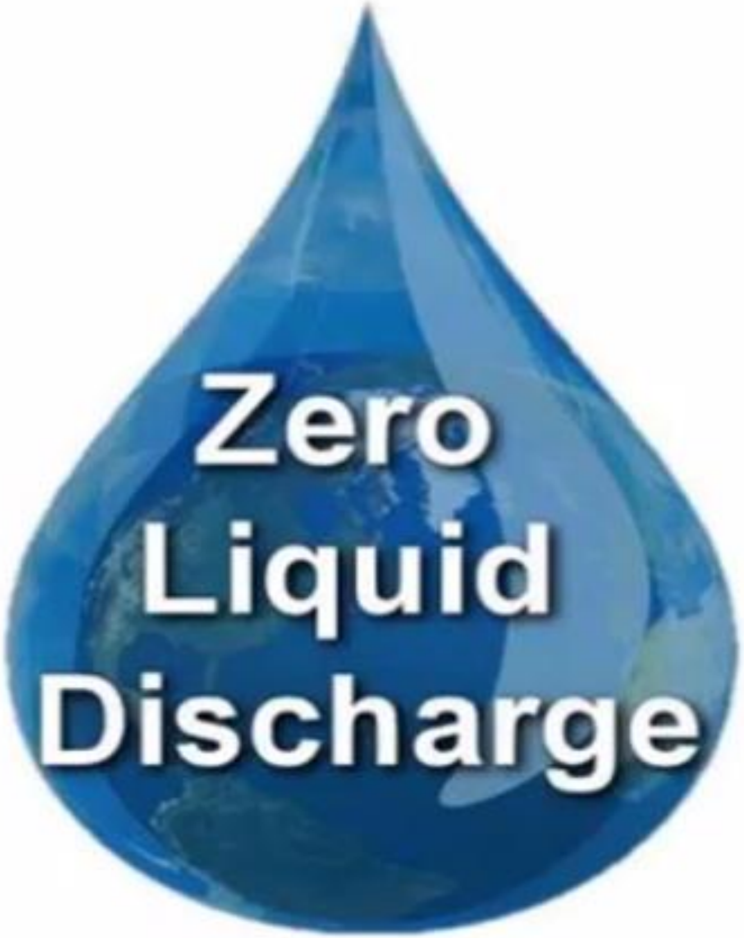
DOC Provides Quick "Backwash" to RO

- Use permeate stored in the DOC vessel to increase pressure on the RO permeate side to same as that in the feed
- Natural osmotic pressure will draw water from the permeate side to the feed side, and hence "backwash"
- Typically twice a day and each lasts ~ 12 sec





Zero Liquid Discharge (ZLD)



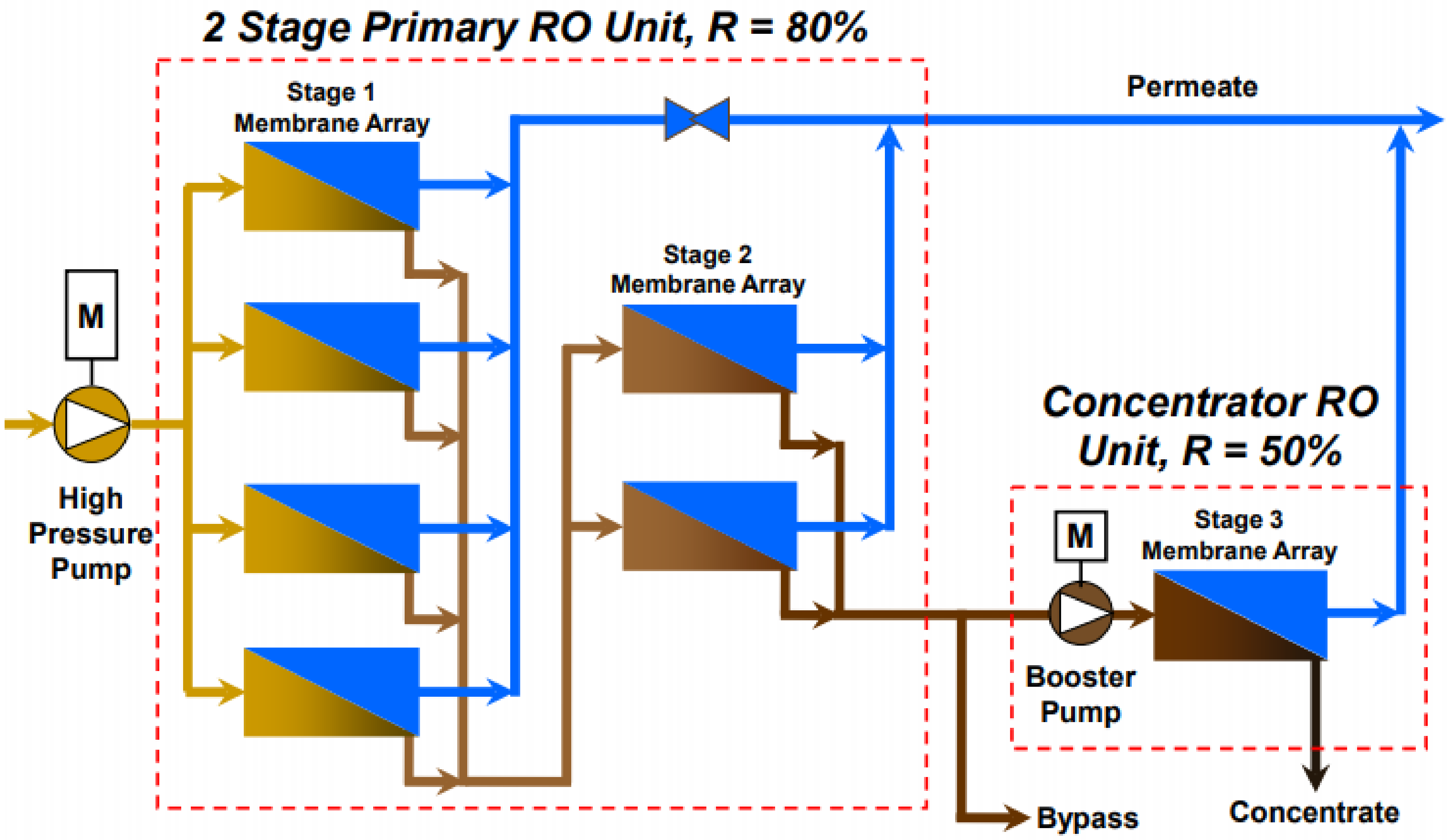
Brackish Water Reverse Osmosis (BWRO) Desalination

- BWRO is primarily used for removing salts from brackish groundwater, such as CaCO3, CaCO4, SiO2, etc.
- These Salts could also form scales and foul the membranes
- Typical BWRO treatment consists of:
  - Pretreatment
  - Salt removal (with BWRO)
  - Post treatment (re-mineralize treated water) to reduce corrosion in the distribution system
- The single biggest challenge to BWRO is how to get rid of the final brine solution (concentrate disposal)

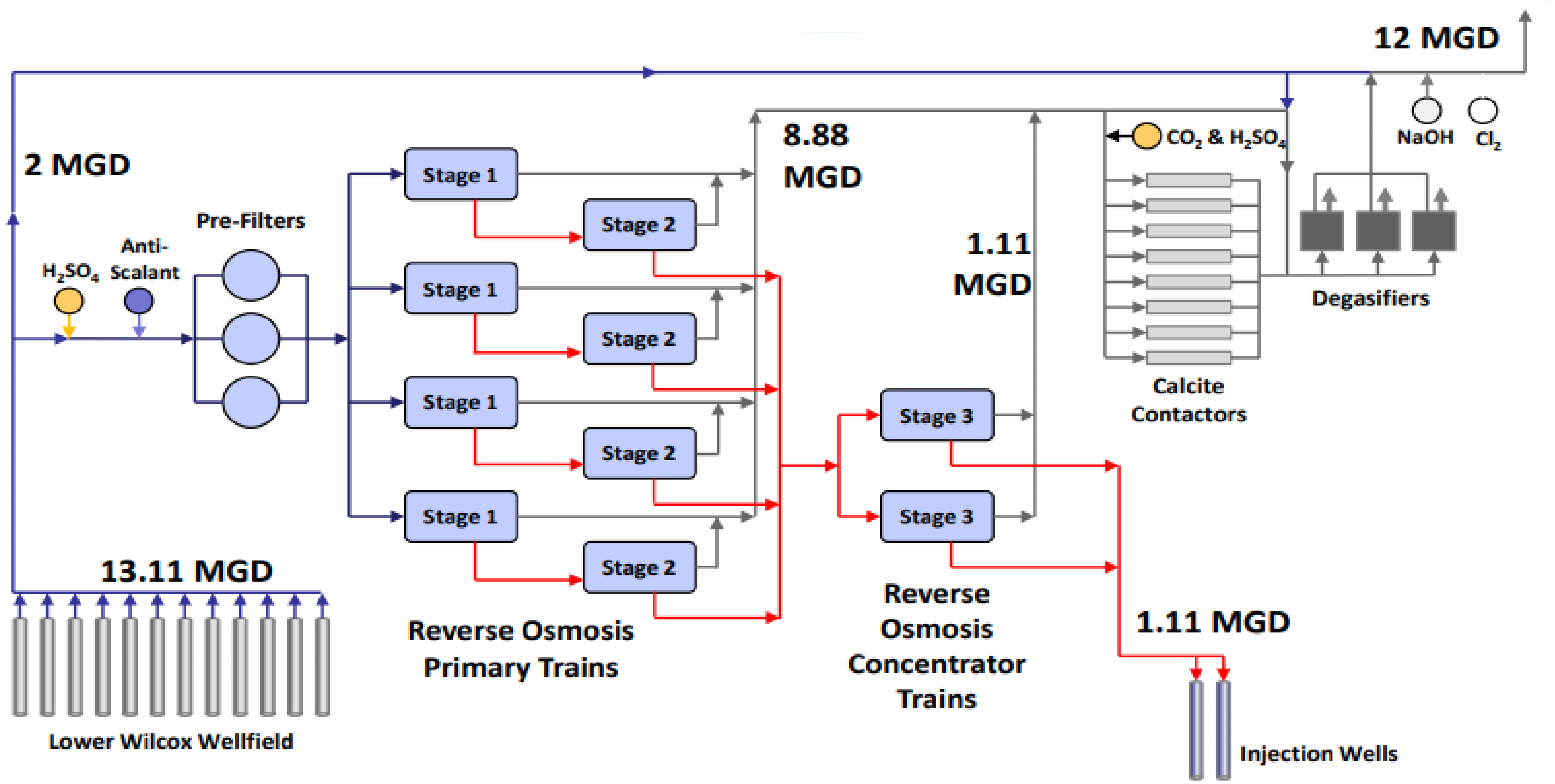
Multi-Stage BWRO Configuration to Maximize RO Recovery

- The only way to minimize brine is to increase recovery by “squeezing” more water out of the BWRO brine
- The only way to achieve higher recovery is to use another set of RO membranes to treat the reject brine, again, therefore the use of “multi-stage BWRO system
- 2 or 3 stage RO is most common
  - # of stages depend on feed water quality
- Brine from 1st Stage is fed to the 2nd Stage
- Brine from 2nd Stage is fed to the 3rd Stage

Conventional 3-Stage BWRO System



Typical PFD for 3-Stage Brackish Desalination



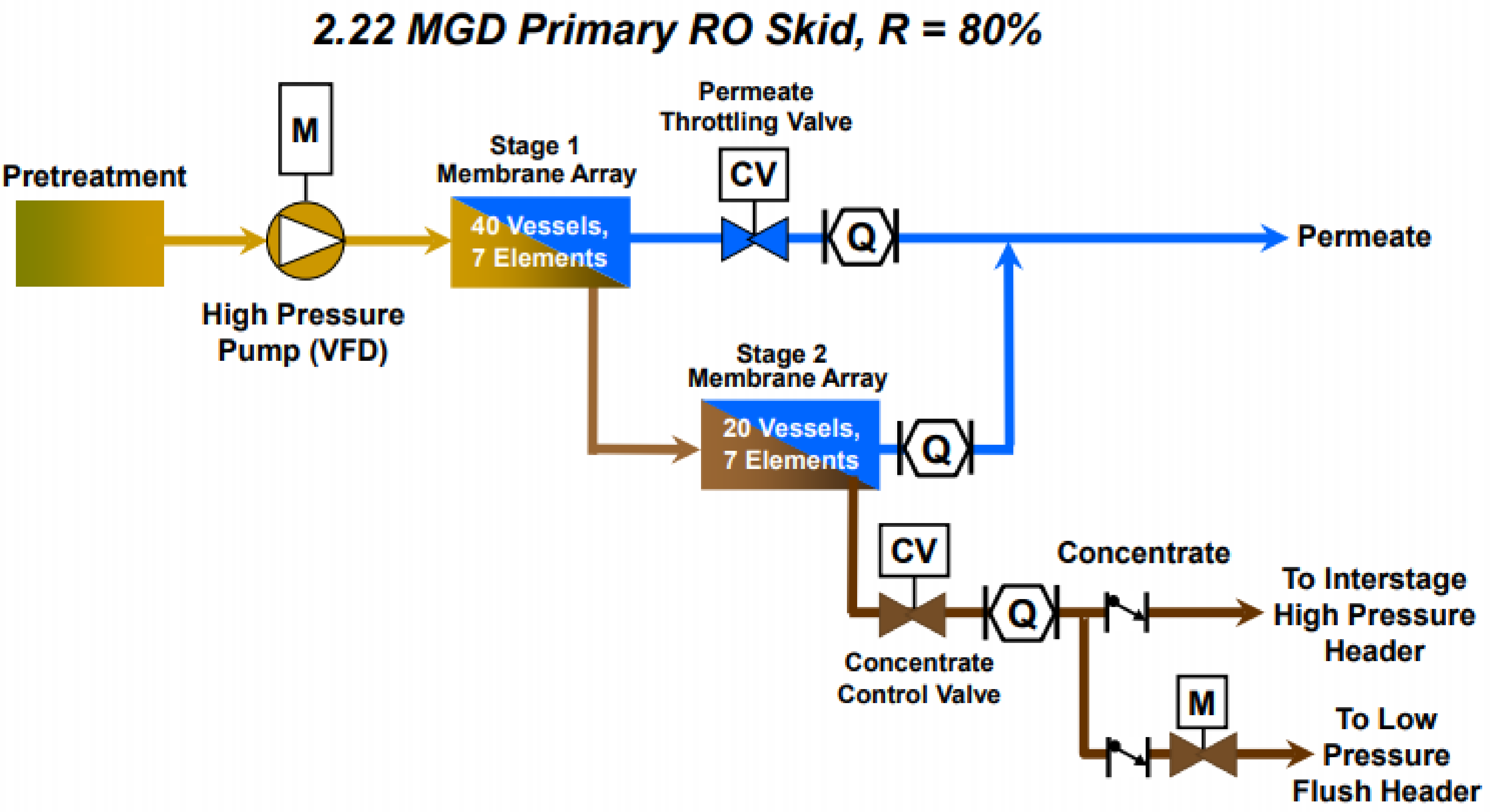
Pretreatment

- Scale Inhibitor/Anti-scalant
- pH Adjustment - 6.5 using sulfuric acid
- Cartridge Filters
  - 3 x 7.0 MGD units
  - 14.0 MGD with one unit offline
  - 5-Micron nominal polypropylene, string-wound, SOE, 40-inch

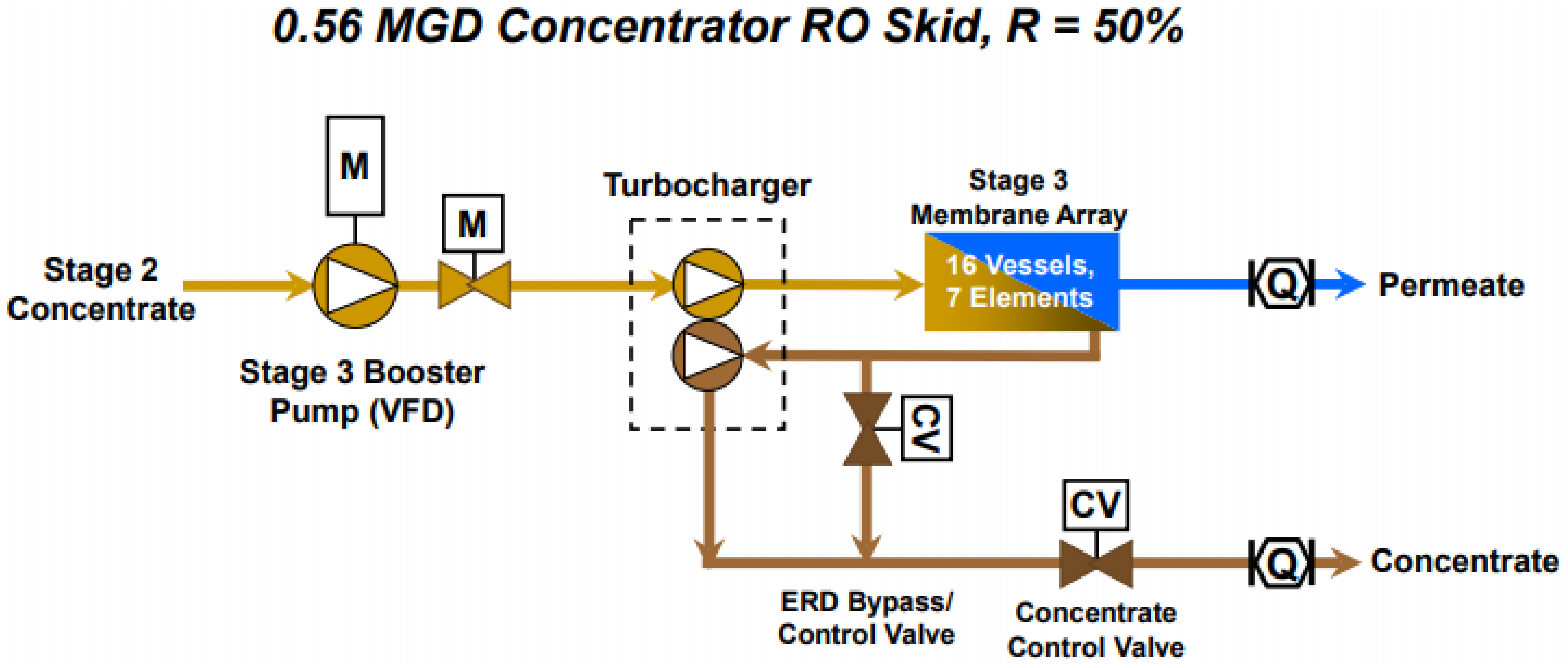
Cartridge Filters

- **DOE –** The most common filter cartridges found are DOE, or Double Open Ended. These cartridges have no built in seals on either end, thus the name. Instead the filter cartridge housing is relied upon to seal one side and stop contaminants from bypassing the cartridge.
- **SOE –** As the name indicates, Single Open Ended cartridges have one end sealed. This seal is usually accomplished by using a polyporpylene cap. By using a cap on one end, filter bypass is impossible, so systems that require higher purity filtration typically implement this type of cartridge filter. The higher cost associated with the end cap prevents this type from being used in general applications.

Primary RO Skid Configuration



3rd Stage Concentrator RO Skid Configuration



Post Treatment

- Calcite Contactors – Calcium and alkalinity addition
- Raw Water Blending – Supplemental alkalinity & hardness
- Degasifiers –Excess CO_2 removal
- Sodium Hydroxide – Final pH stabilization
- Chlorine – Disinfection

Raw Water Blend (Bypass) Control Valve

Injection Well for Concentrate Disposal

- 2 Injection Wells
- Injection Well Details:
  - Well Depth: Approx. 5,100 ft
  - Avg. Flow: 500 gpm (30 day avg)
  - Instantaneous Flow: 1,000 gpm
  - IW Pressures: 775 psi max, 150-250 psi at 385 gpm
  - Injection Zone TDS: 90,000 mg/L
- First Class 1 UIC General Discharge Permit issued by TCEQ for RO Concentrate Disposal

Question #1: What’s the color?

Design Considerations for Production Wells

Silica and Iron

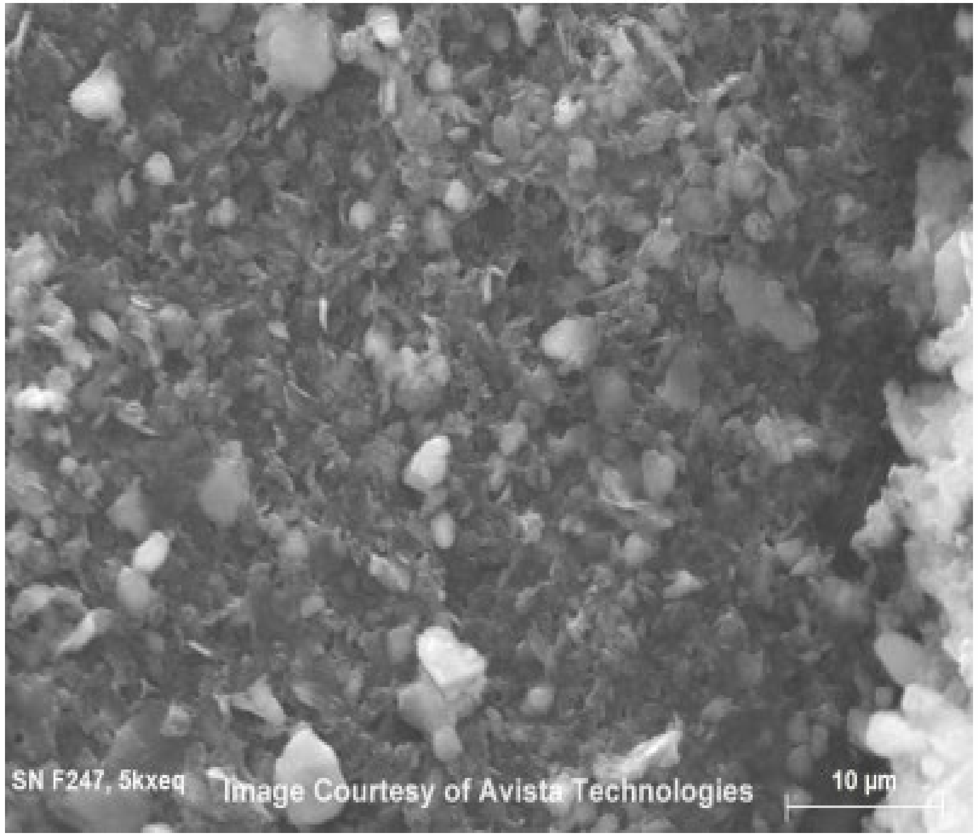
- Due to higher design recovery, both Iron and Silica were concerns from initial well data
- More than 50% of iron is maintained in dissolved form
- Cause of partial iron oxidation (measured at well) is uncertain
  - Low amounts of DO are present in raw water at the wellhead
  - ORP is consistently negative (-150 to -200 mV)
  - No clear correlation between oxidized iron, DO, and ORP
- Well operational pre-flushing is necessary
- Well pump speed control philosophy has proved to provide stable and reliable control
- Raw water entering the plant maintains a negative ORP

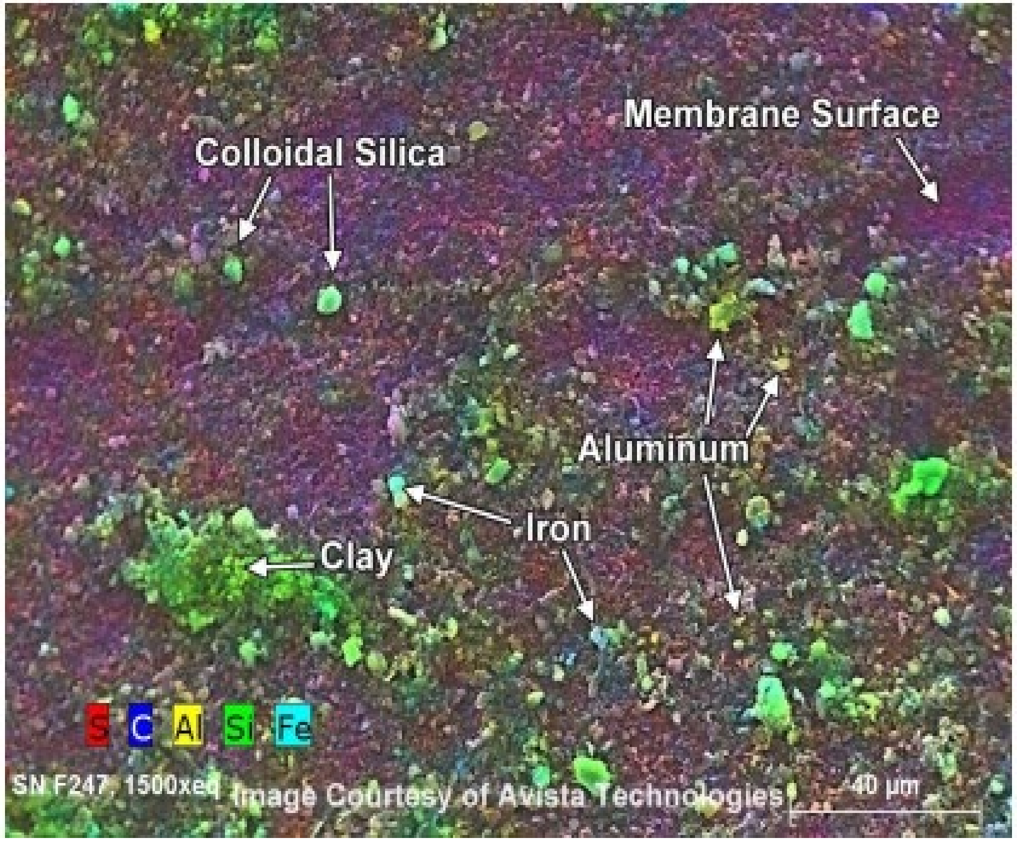
Supply Well Water Quality Monitoring

- SDI (Silt Density Index)
- Overall raw water quality (SDI & turbidity) appears to be improving over time
- However, some wells still produce higher turbidity and SDI despite of flushing
- WQ monitoring needs to continue for a substantial period of time

SEM & CEI Images of Fouling Materials

- Fe, Al, Colloidal Silica and Clay are the primary fouling material





Clean In Place (CIP) System

- Two 900 GPM Cleaning Pumps, VFD Controlled
- Two 5,000 Gallon Mixing Tanks
- Cleaning Capacity: Entire 1st stage (40 vessels)
  - Upsized piping and tanks
  - Hard-piped to RO skids
- Accessibility: Catwalk tank access for chemical loading from mezzanine storage area
- System Flexibility:
  - Immersion heaters and mechanical mixers on both tanks
  - Cleaning pumps can recirculate tanks for mixing or transfer solutions

Post Treatment with Calcite Re-Mineralization System

- 30% Side Stream of 10 MGD of RO Permeate =
  - 3.0 MGD for Phase I (12 MGD finished water)
  - 7.5 MGD (3.75 MGD x 2) at Buildout (30 MGD finished water)
- TomCO Pressurized Solution Feed System (PSF)$_{TM}$ used for efficient CO2 feed to the influent water stream
- Sulfuric acid feed for supplemental pH adjustment and backup to CO2

Calcite Contactor System Design

Design Parameter	Design Criteria
Number of Units	8 (7 + 1 Standby)
Contactor	Pressurized, Up-Flow
Contactor Diameter	12-feet
Calcite Bed Depth	9-feet
Design EBCT	17 minutes (at 4 gpm/ft^2)
Maximum Loading Rate	6.5 gpm/ft^2
Influent pH	5.0 SU
Design Flow Rate	372 gpm (0.53 MGD)
Forward Flush Design Flow	1,700 gpm
Air Scour	600 CFM

Re-Mineralization Efficiency Depends on Calcite Media

- Limited suppliers of NSF 60 Calcite in US. None are currently in Texas, so must be sourced from out of state suppliers.
- Should consider freight costs and lead time. Bulk delivery sizes are not always the same.
- Media is naturally sourced, with wide variety of particle size, distribution, and calcite purity
- Design and operation of system is significantly affected by the media that will be used:
  - Finer (smaller) media size will dissolve faster but can more easily be carried out of column at high loading rates, leading to increased turbidity
  - Courser (larger) media size will fluidize much differently than finer media, will require a deeper media bed.

3,000 lb. Calcite Super Sacks

Finished Water Quality

Parameter	Overall Finished Water Quality Goal	BGD Finished Water Parameters
pH, Std Units	7 – 8.5	7.9 – 8.2
TDS, mg/L	< 400	< 320
Alkalinity, mg/L as $CaCO_3$	100 – 300	120- 160
Calcium, mg/L as Ca (mg/L as $CaCO_3$)	40 – 100 (100 – 250)	38 – 46 (95 – 115)
LSI	0.1 – 0.4	> 0.1 (at 25 °C)
CCPP, mg/L as $CaCO_3$	4 – 10	7 – 12 (at 25 °C)

Understanding Langelier Saturation Index (LSI)

- An Index that predicts whether calcium-based solids will tend to precipitate, or dissolve in a specific water chemistry

LSI = (pH) + (Temperature) + (Calcium Hardness) + [(Total Alkalinity) – (CYA Correction Factor @ current pH)] – (TDS Factor)

- If LSI > 0, solid tend to precipitate
- If LSI < 0, solid tend to dissolve
- We like finished water having LSI slightly positive to avoid corrosion

Equivalent Factors for Langelier Saturation Index (LSI)

Equivalent Factors - Langelier Saturation Index (LSI)

Temperature (°F)	Temperature Factor	Calcium Hardness (PPM)	Calcium Hardness Factor	Alkalinity (PPM)	Alkalinity Factor	Cyanuric Acid (if present)	Cyanurate Correction Factor	Total Dissolved Solids	TDS Factor
32	0.0	5	0.3	5	0.7	**pH**	**Factor**	< 1000 ppm	12.10
37	0.1	25	1.0	25	1.4	7.0	0.23	1000 ppm	12.19
46	0.2	50	1.3	50	1.7	7.2	0.27	2000 ppm	12.29
53	0.3	75	1.5	75	1.9	7.4	0.31	3000 ppm	12.35
60	0.4	100	1.6	100	2.0	7.6	0.33	4000 ppm	12.41
66	0.5	150	1.8	150	2.2	7.8	0.35		
76	0.6	200	1.9	200	2.3	8.0	0.36		
84	0.7	300	2.1	300	2.5	Note: Only use if CYA is used in your pool. Only applies to >7.0pH. If so, select correction factor based on pool pH.		Note: most calculators assume **12.1** for under 1000ppm, or **12.2** for anything over 1000.	
94	0.8	400	2.2	500	2.6				
105	0.9	800	2.5	800	2.9				

Q2: What's the number?

Example of LSI Calculations

- Water pH = 7.4
- Water Temp = 84F (0.7)
- Calcium Hardness: 300 (2.1)
- Alkalinity: 100 (2.0)
- TDS: < 1,000 (12.1)

Calculation:

- LSI = [7.4 + 0.7 + 2.1 + (2.0 – 0.31) – 12.1]

  = 10.2 + 1.69 – 12.1

  = - 0.21

- This water is slightly corrosive. Adjusting pH to 7.8 will make LSI to be 0.19, which is slightly possitive

Final BWRO Brine Disposal

- Evaporation Pond is cost-prohibitive for BWRO Brine Disposal due to very high construction costs; particular with the underlined barrier and monitoring for leakage & repair