2.500 Desalination and Water Purification
Spring 2009

2.500 Desalination & Water Purification

Slides to accompany reverse osmosis discussion

3 March 2009

Professor John H. Lienhard V

Department of Mechanical Engineering
Massachusetts Institute of Technology

Spiral-wound element

20 cm diam by 1 m length

Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

Source. This image and many of the subsequent images are from:

M. Wilf and M. Balaban, *Membrane Desalination and Membrane Filtration*, L'Aquila, Italy: European Desalination Society, 2007.

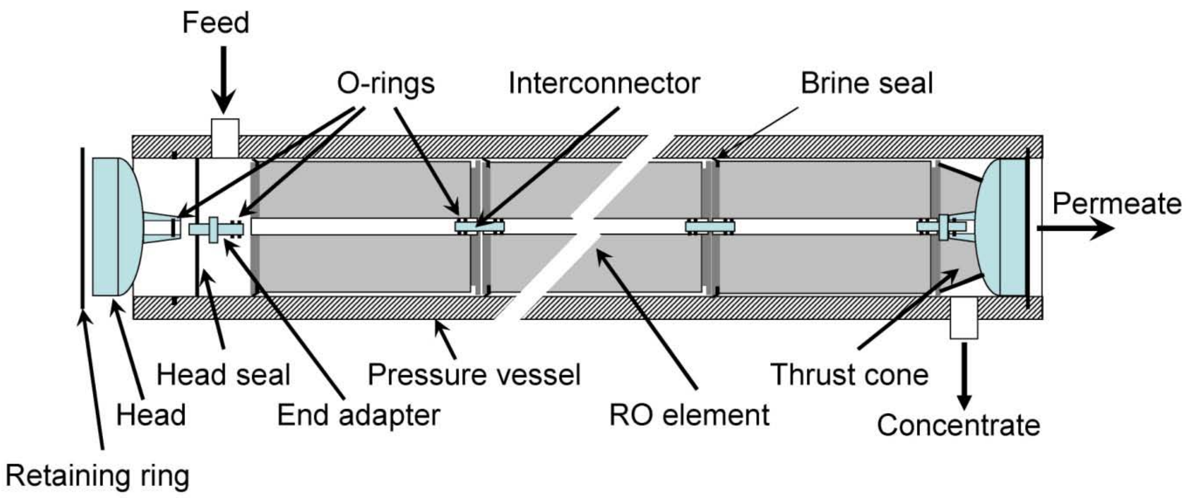
Reduced Membrane Pricing

Year	Element Price	Price ft^2	Normalized Price/Area	CPI	1978= 1 CPI	Norm 78 Price/Area
1978	$950	$6.33	1	71	1	1
1989	$875	$2.92	$0.46	124	1.75	0.26
1995	$750	$2.27	$0.36	152	2.14	0.17
2000	$645	$1.79	$0.28	172	2.42	0.12
2002	$435	$1.18	$0.19	180	2.54	0.07
2006	$550	$1.38	$0.22	200	2.82	0.08

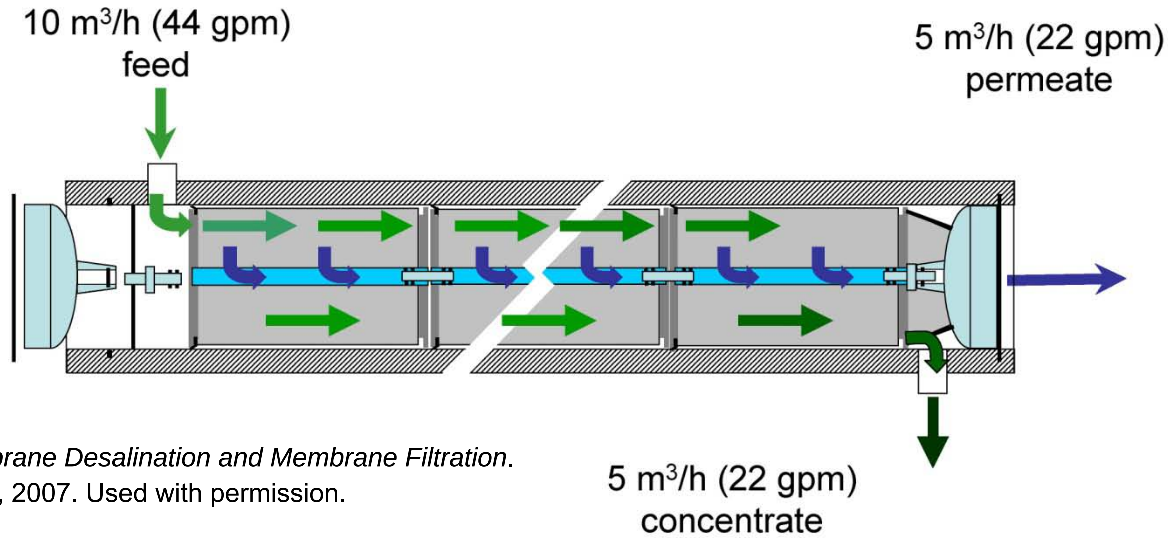
J. Birkett & R Truby, 2007

Source: Leon Awerbuch, desalination lecture at MIT, 23 Feb 2009

Configuration of a pressure vessel assembly



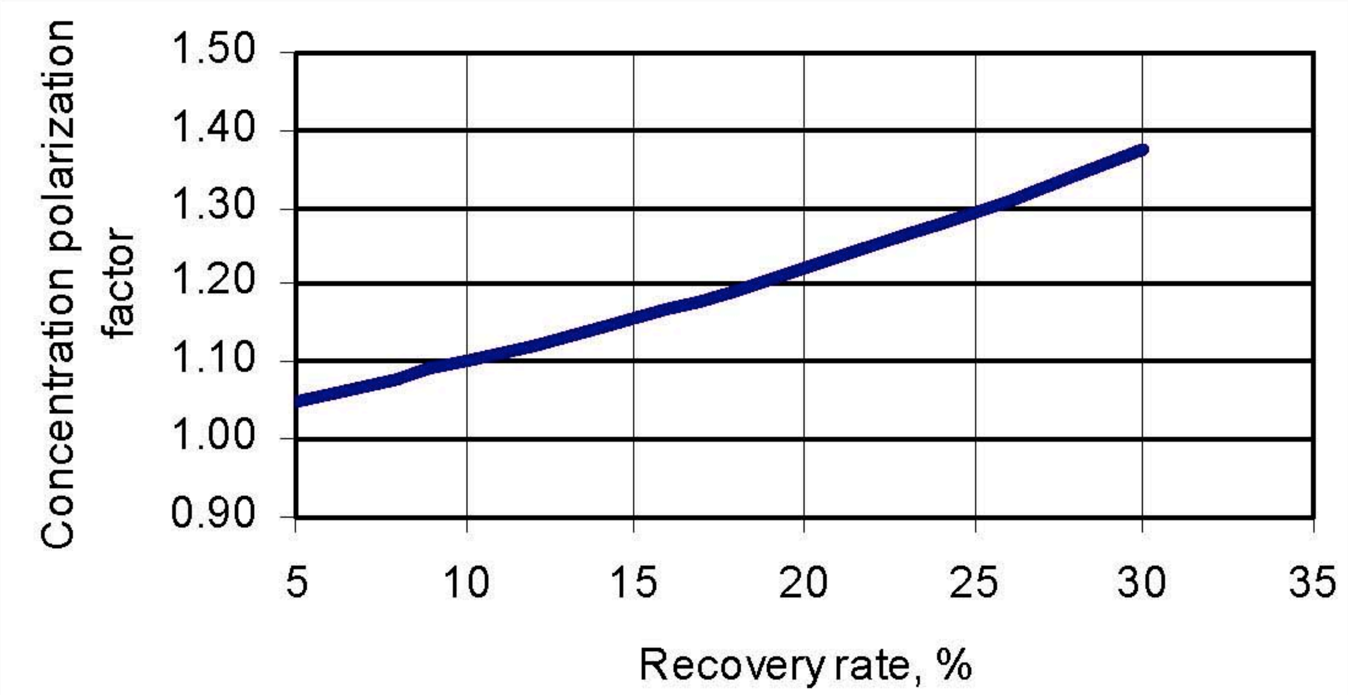
Water flow in a pressure vessel assembly



Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*.
L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

Vertical centrifugal pumps & Membrane pressure vessels



Relative concentration polarization factor vs. membrane element recovery rate. $\beta = \exp(0.75 \cdot 2R/(2 - R))$

Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

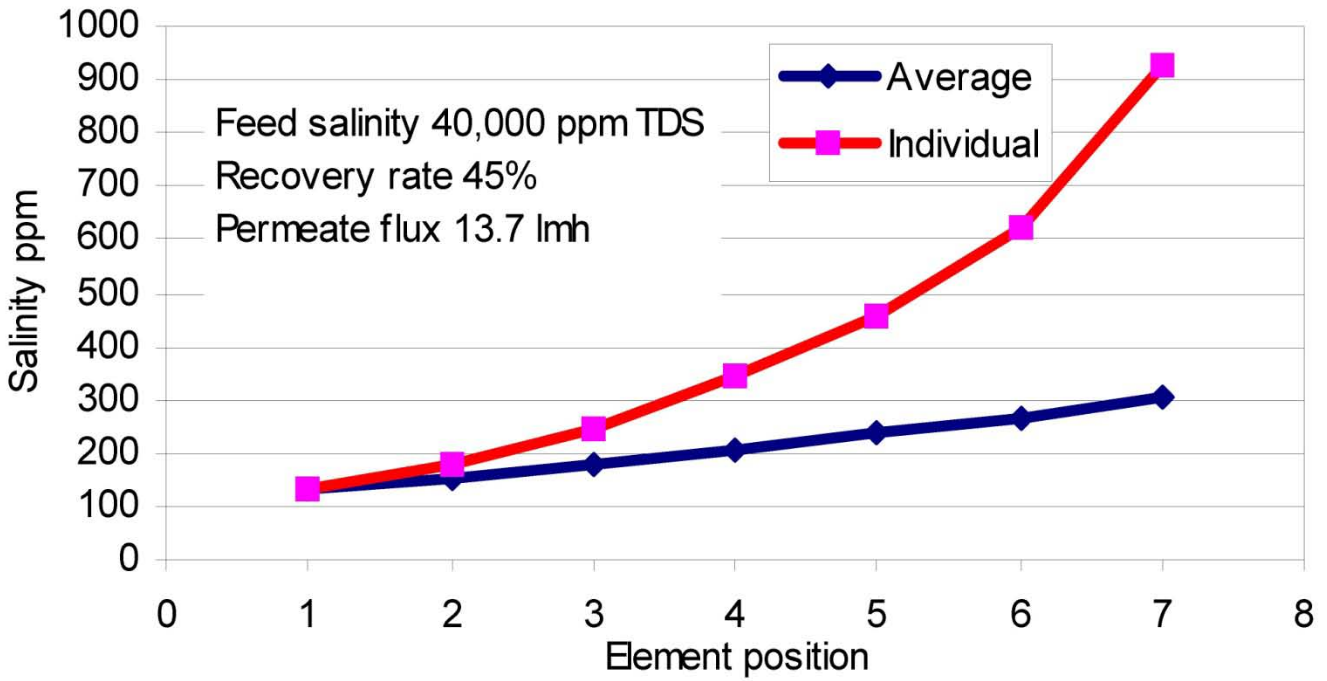
Recovery per element is limited to about 18% to prevent excessive concentration polarization

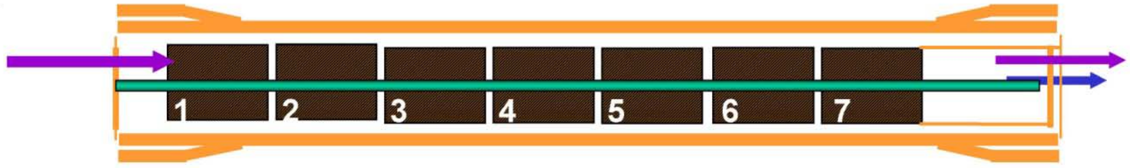
Recovery rate of individual elements in a pressure vessel. Seawater RO, R = 50%

Element position	6 elements/vess. Recovery, %	7 elements/vess. Recovery, %	8 elements/vess. Recovery, %
1	16.1	15.1	13.2
2	15.3	12.9	12.5
3	11.3	11.0	11.1
4	10.2	8.3	8.9
5	8.5	6.8	7.8
6		4.9	6.3
7		5.1	4.5
8			2.3

Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

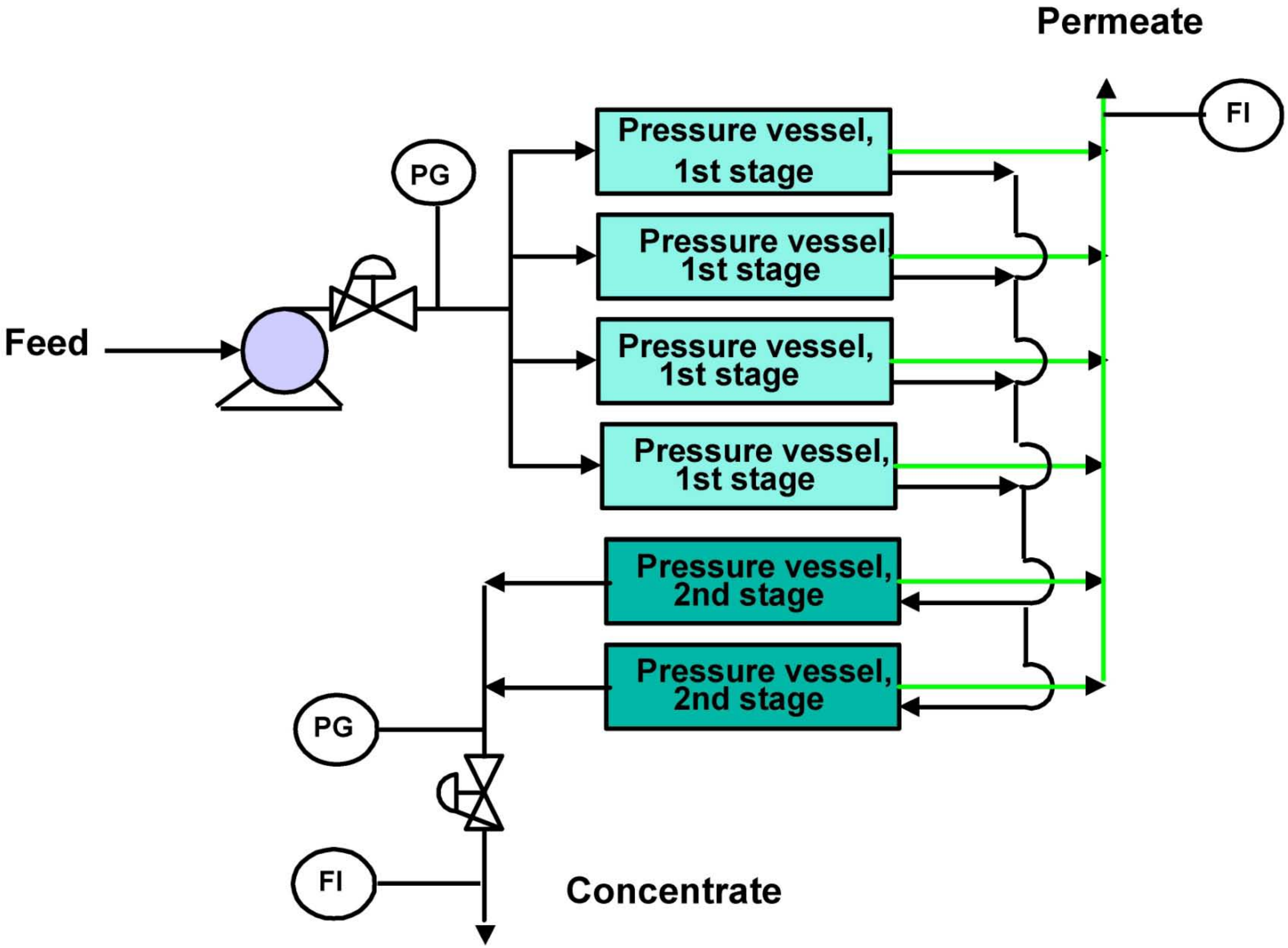
Seawater system, salinity distribution





RO elements in a pressure vessel.

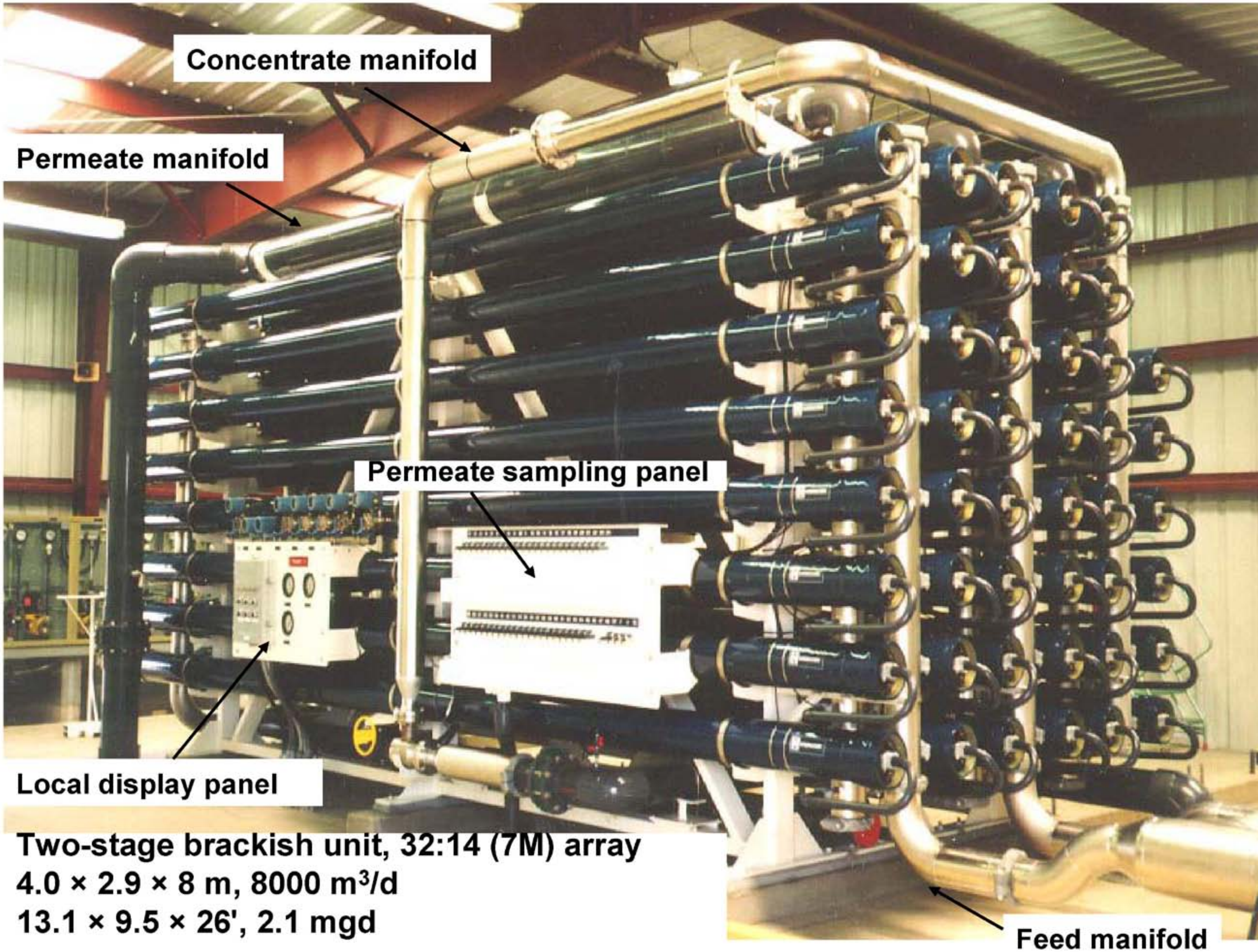
Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.



Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

Concentrate may be staged in order to achieve high recovery without excessive concentration polarization, e.g., in brackish water RO (BWRO)

$R_{p,1\ stage} \lesssim 60\%$ $R_{p,2\ stage} \lesssim 75\text{-}85\%$



Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

First stage has 32 pressure vessels; second stage has 14

Location	1	2	3	4	5	6	7	8	9
Flow, m^3/h (gpm)	521.3 (2294)	521.3 (2294)	184.9 (814)	184.9 (814)	104.2 (458)	336.0 (1478)	80.7 (355)	416.7 (1833)	104.2 (458)
Pressure, bar (psi)		17.1 (248)	14.2 (206)	23.2 (336)	20.8 (302)				0.5 (7)
TDS ppm	5881	5881	16313	16313	28444	139	657	240	28444

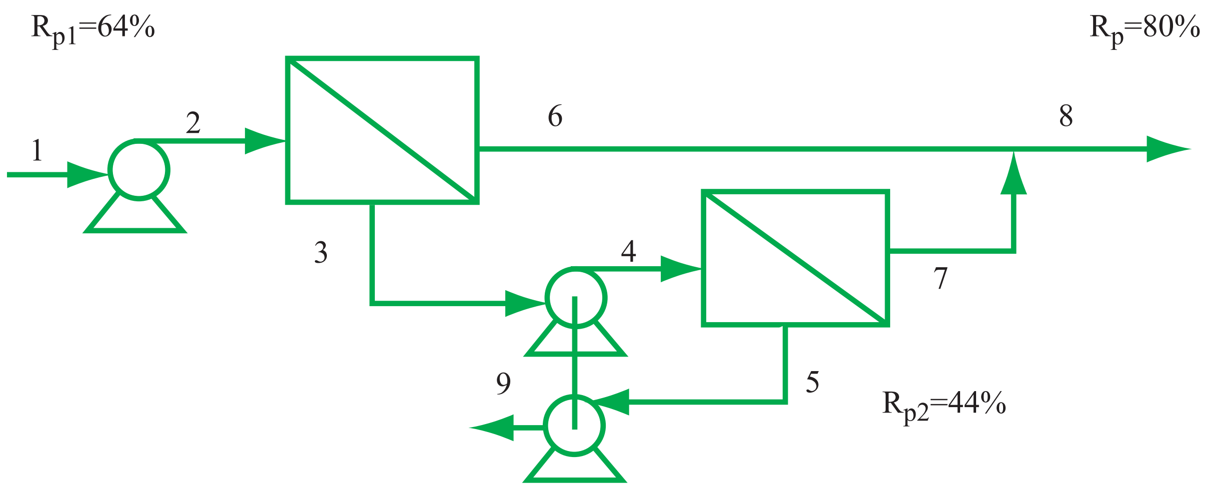
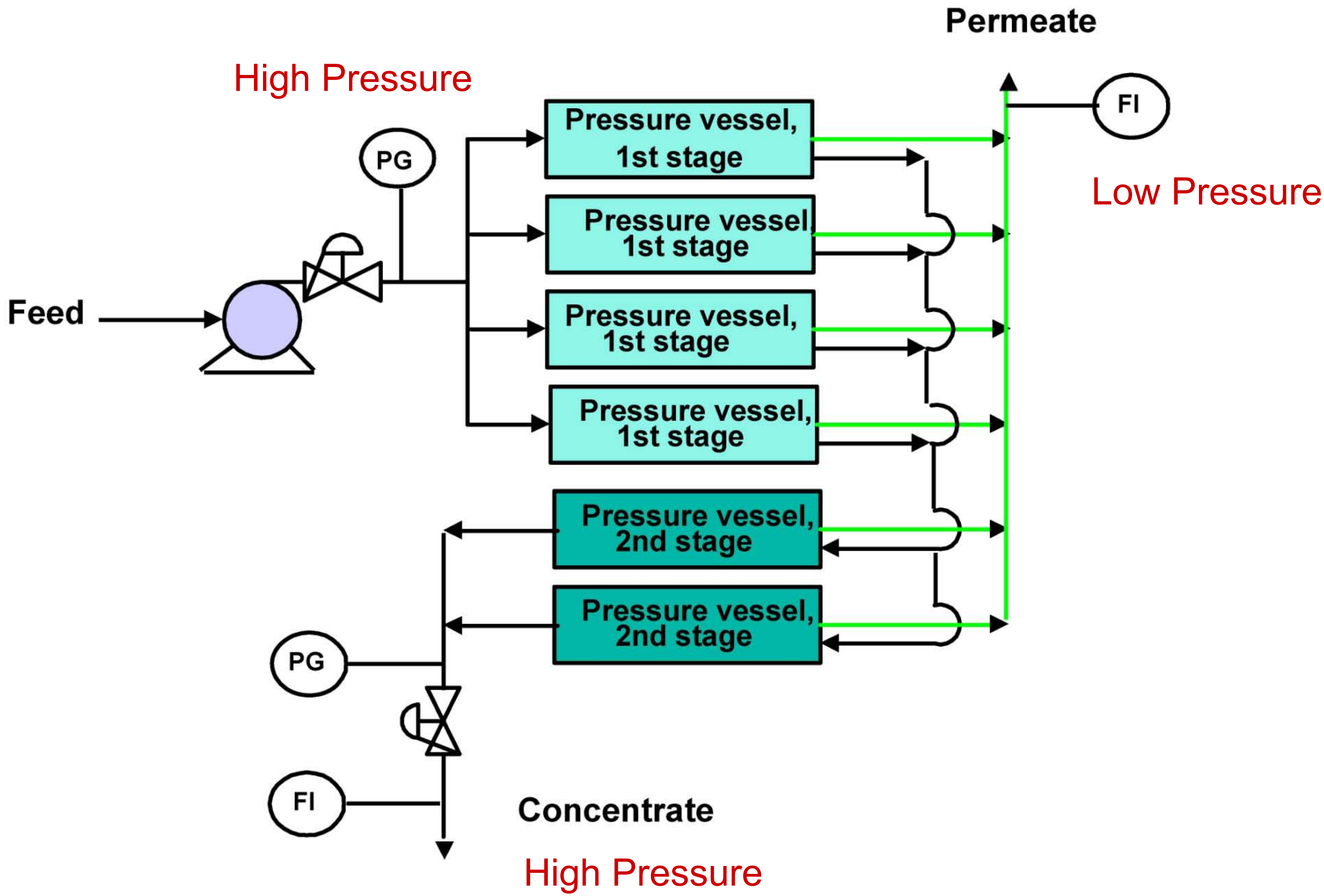


Figure by MIT OpenCourseWare.

Concentrate staging in a high-salinity brackish RO system with 80% recovery. Note turbine assisted booster pump.

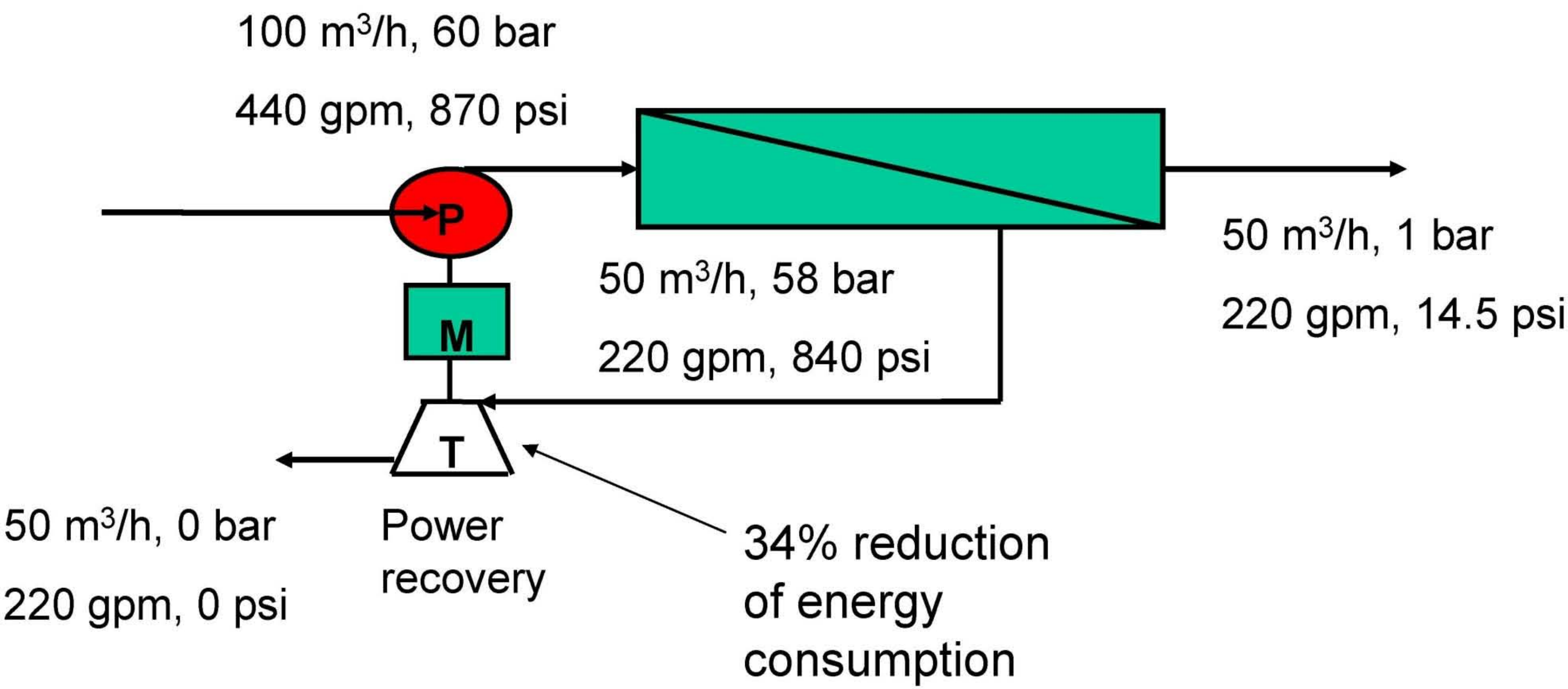


Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

Pumping power = (Volume flow rate) * (pressure rise)

The high pressure concentrate accounts for a large part of the pumping power

High pressure pump with Pelton wheel



Energy consumption of RO process: 2.60 kWh/m^3 (9.84 kWh/kgallon)

Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

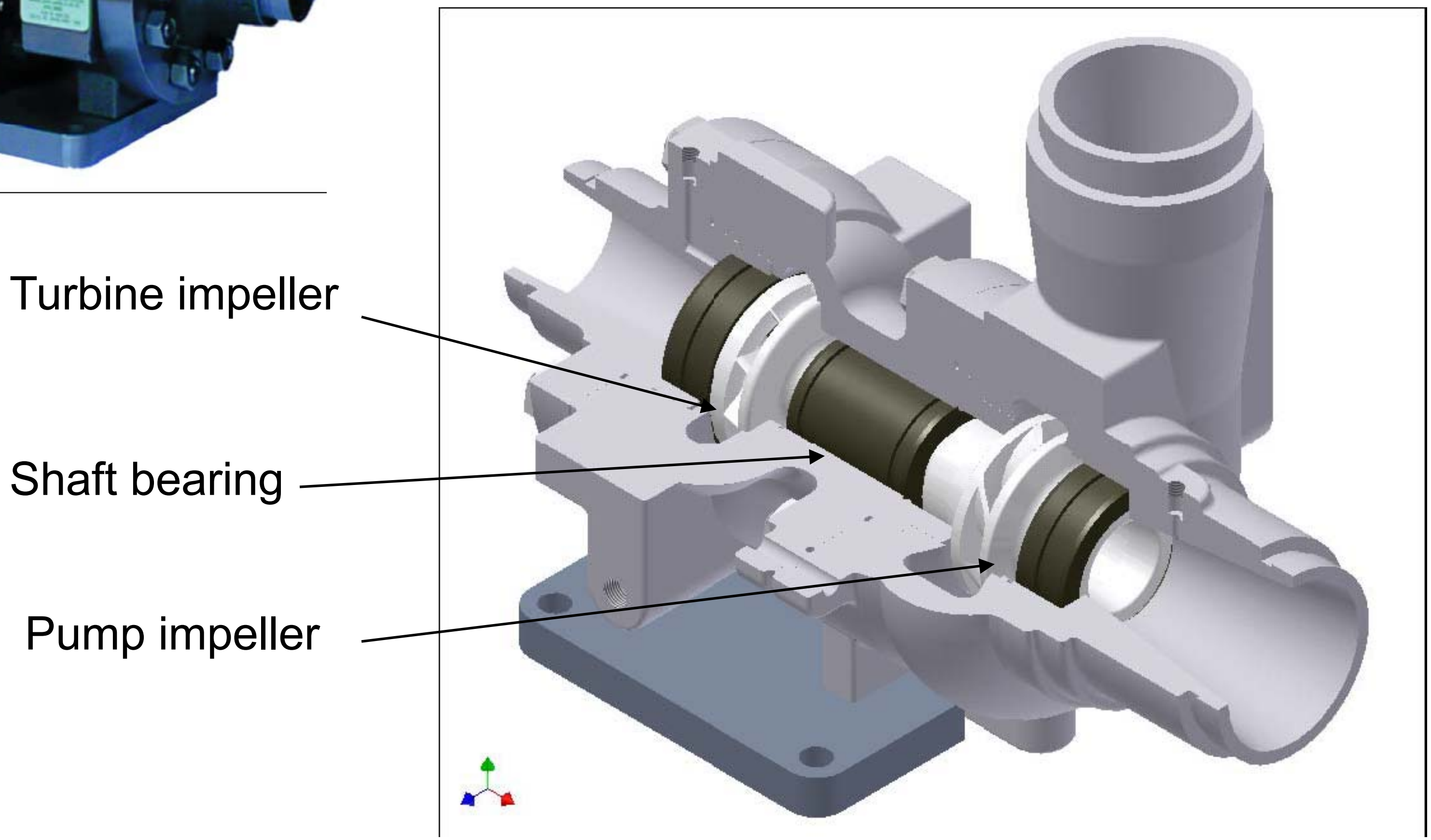
Pumping system at Larnaca plant. (Cyprus)

Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

Pelton Wheel

Energy recovery device



Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

Turbocharger applied as interstage booster pump

Location	1	2	3	4	5	6	7
Flow, m^3/h (gpm)	657.4 (2893)	490.6 (2159)	166.8 (734)	490.6 (2159)	73.5 (323)	416.7 (1833)	583.5 (2567)
Pressure, bar (psi)				8 (116)	3.3 (48)		
TDS, ppm	647	647	647	647	4107	41	215

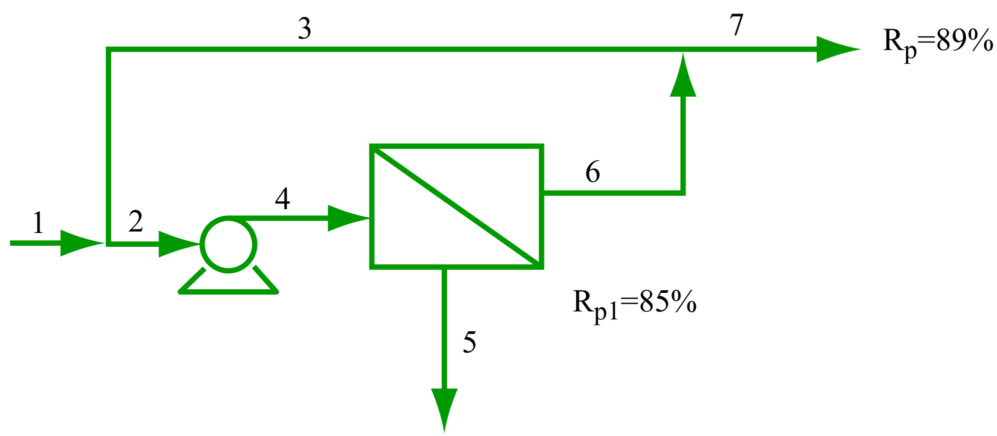


Figure by MIT OpenCourseWare.

Permeate blending in a low-salinity brackish RO system with 89% recovery

Permeate may be blended to lower feed salinity in SWRO

Location	1	2	3	4	5	6	7	8	9	10
Flow, m^3/h (gpm)	979.0 (4308)	992.2 (2159)	992.2 (4369)	575.5 (2534)	138.9 (611)	138.9 (611)	13.9 (61)	125 (550)	277.8 (1222)	402.8 (1772)
Pressure, bar (psi)			64.4 (934)	62.8 (911)		10.7 (155)	7.1 (103)			
TDS, ppm	45199	44695	44695	76707	977	977	9153	68	245	190

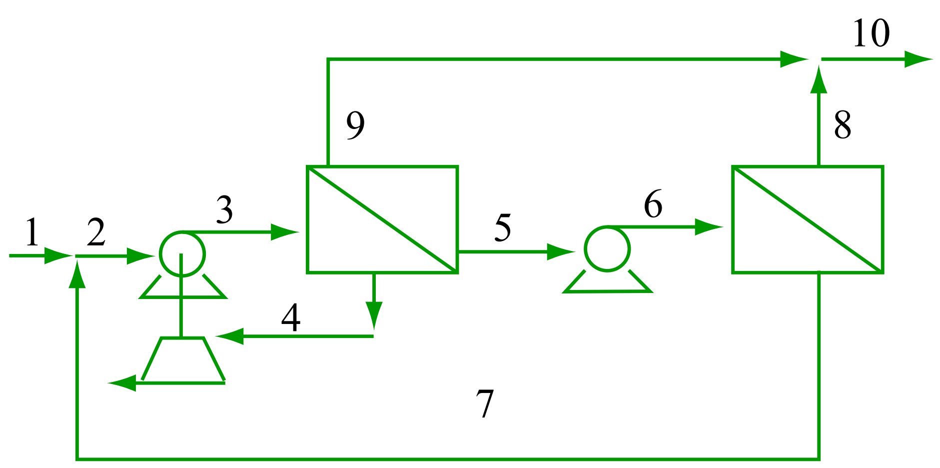
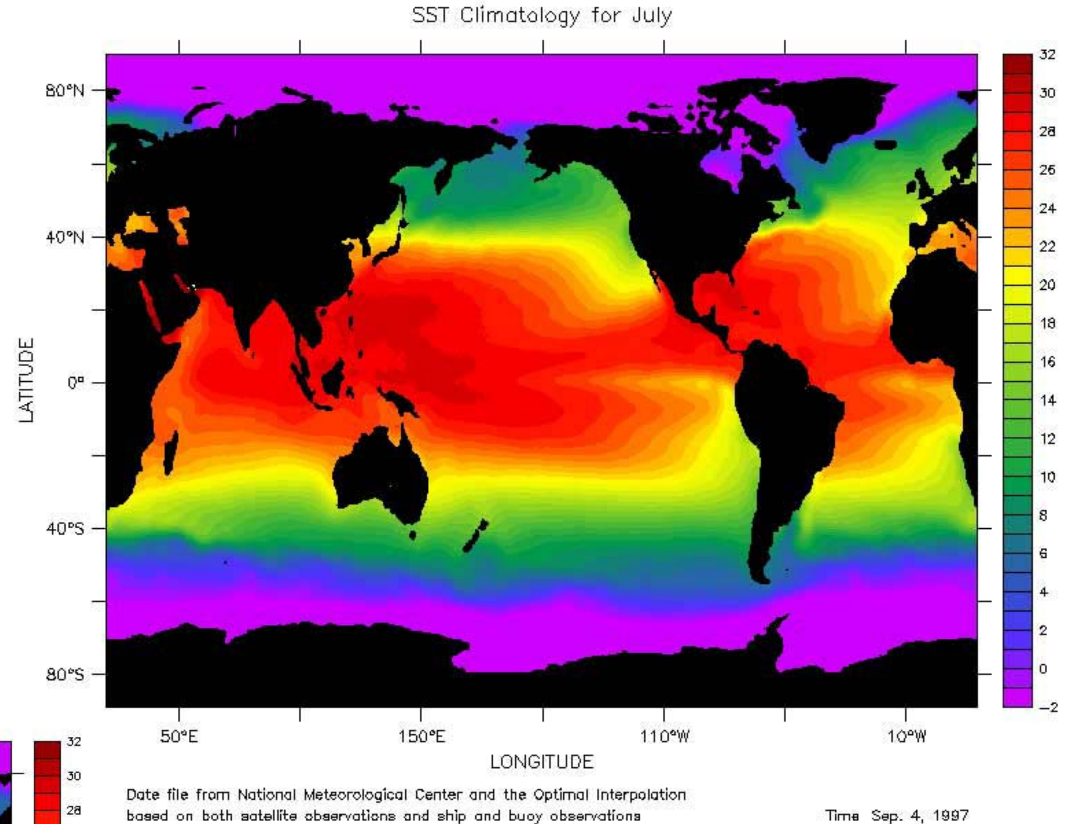
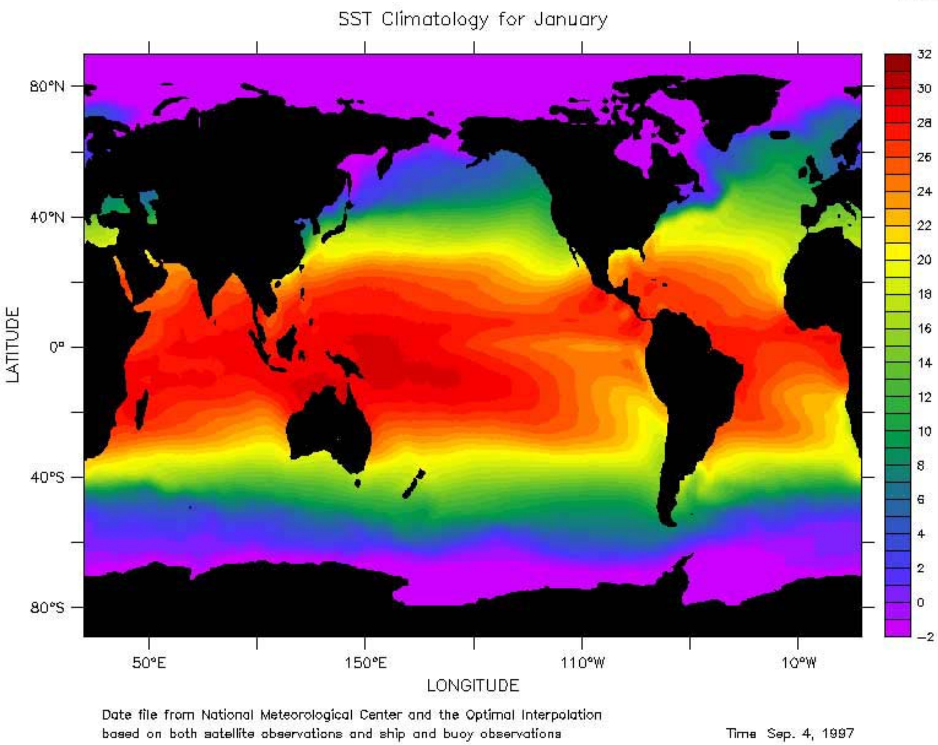


Figure by MIT OpenCourseWare.

Ocean surface temperatures in July and January





Source: R.H. Stewart, *OceanWorld* website, TAMU.

Correction for temperature change

Membrane permeability (for both water and salt) rises with temperature: $P = P_0 \exp(-E/RT)$

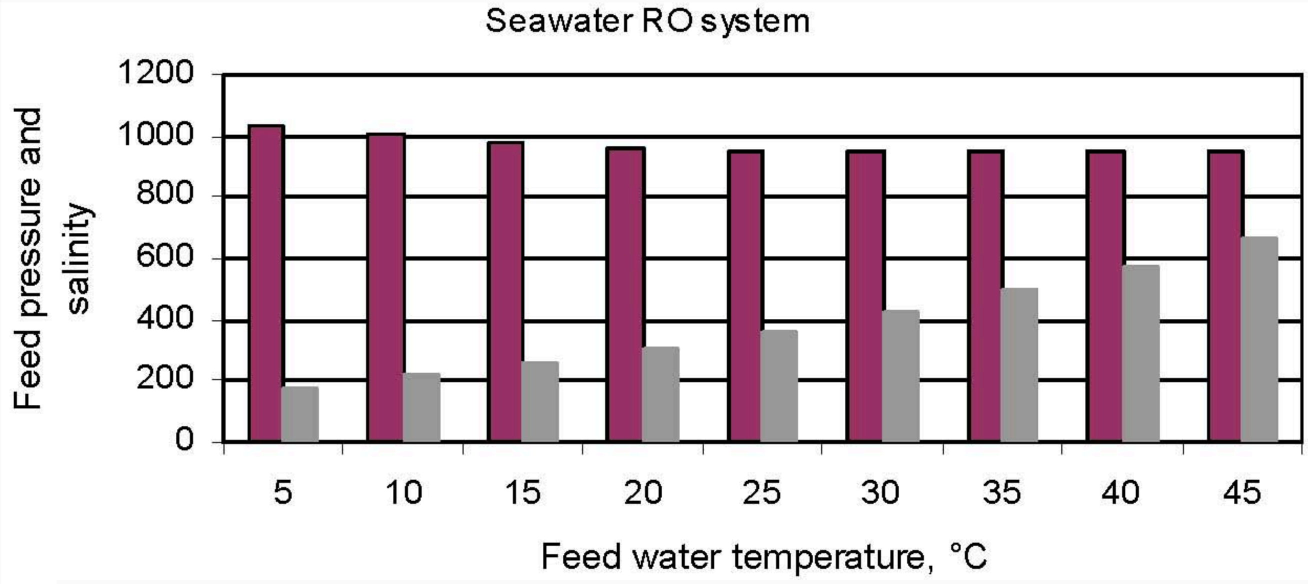
Temperature correction factor (representative):

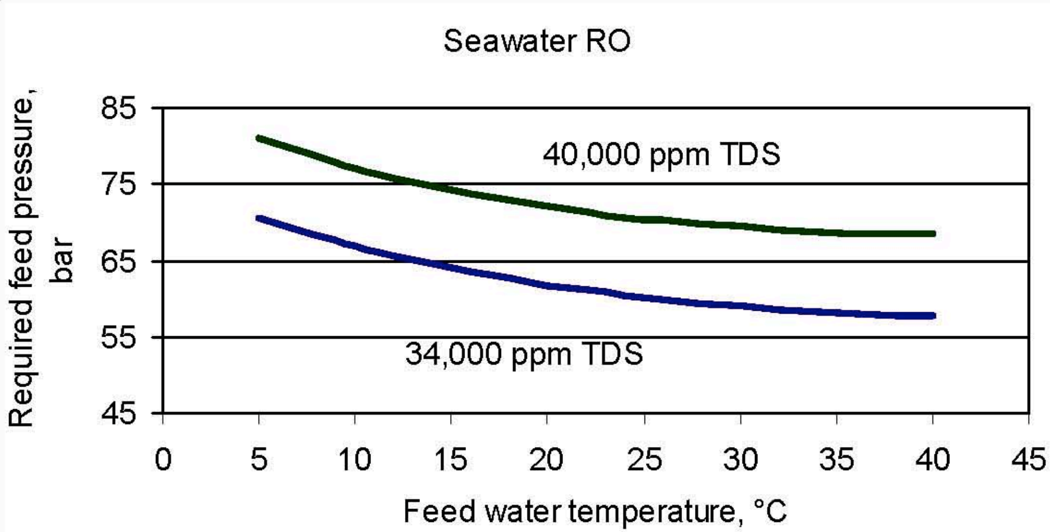
$$TCF = \exp[-2700(1/T - 1/298)]$$ for T in kelvin.

Both A and B in solution-diffusion model are multiplied by the TCF.

TFC = 1 at T=298 K. TCF rises with increasing temperature.

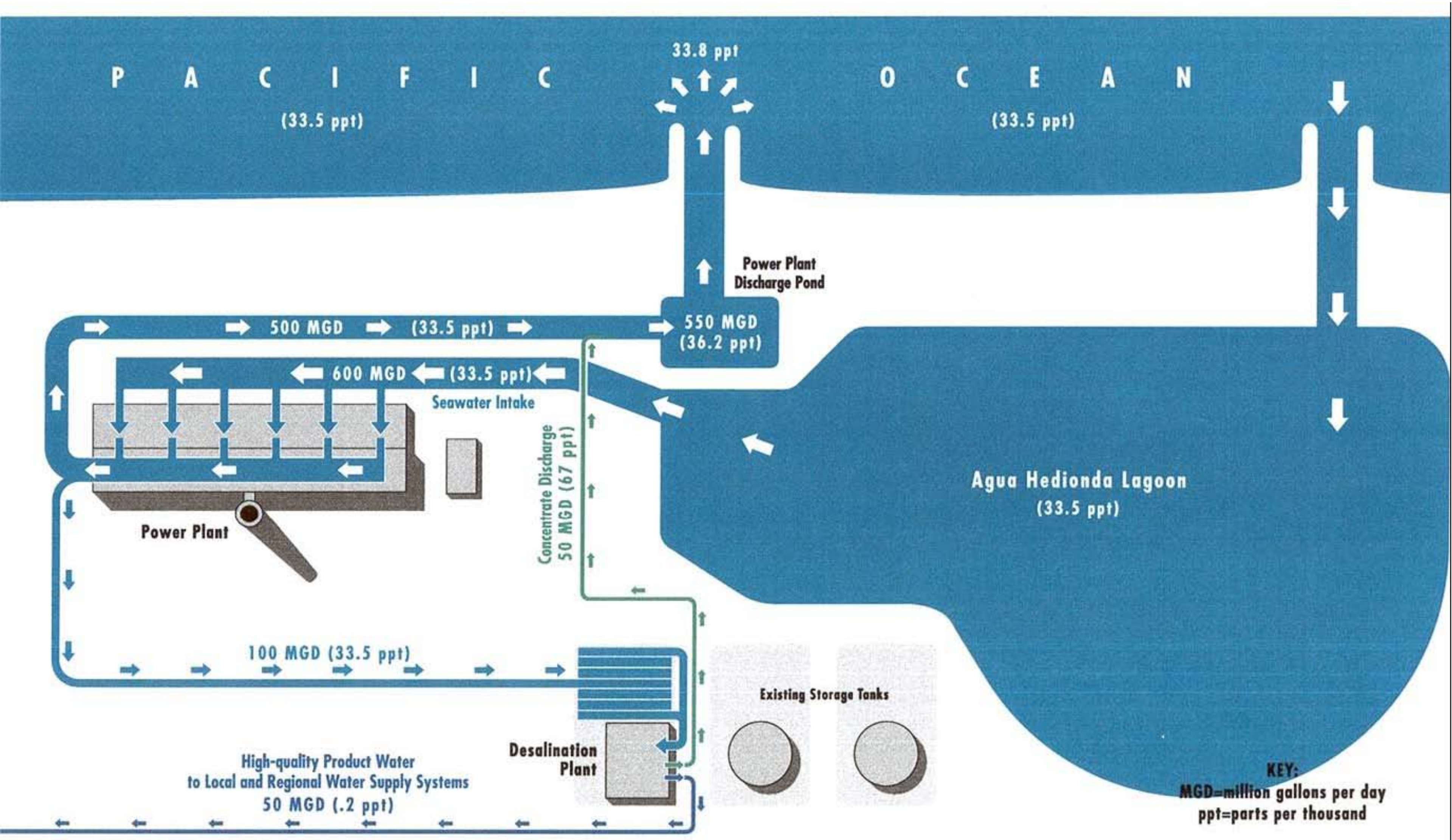
(at fixed flux)





Effect of feed water temperature on required feed pressure in a seawater RO unit, recovery 50%, flux 14 l/m^2-h.

Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.



Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

Feedwater preheating can be beneficial, especially if supply is relatively cold.

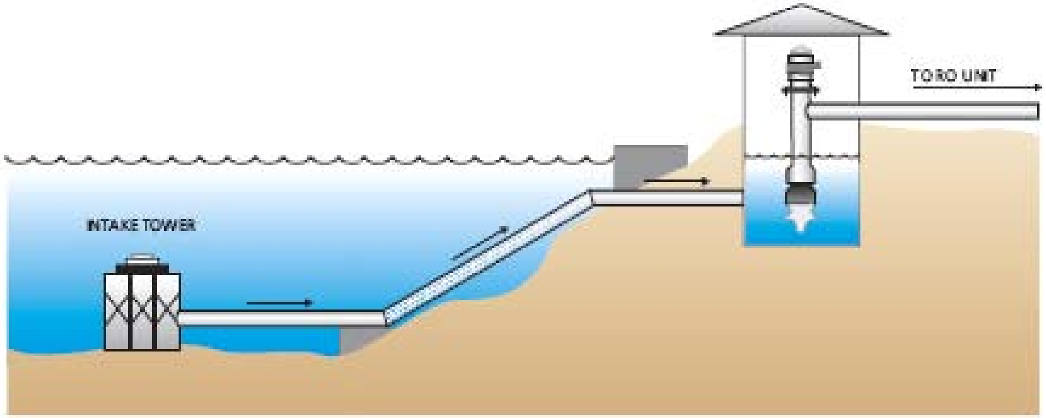
Image removed due to copyright restrictions.
Please see http://www.tsgwater.com/images/specs_10k.pdf

This 10,000 gpd (38 m^3/day) system costs ~$40K. With ancillary hardware, it is ~$60K, plus site preparation and related costs.

A 100,000 gpd (380 m^3/day) system is ~$600K, with ancillary systems.

Typical applications include Caribbean resorts and hotels.

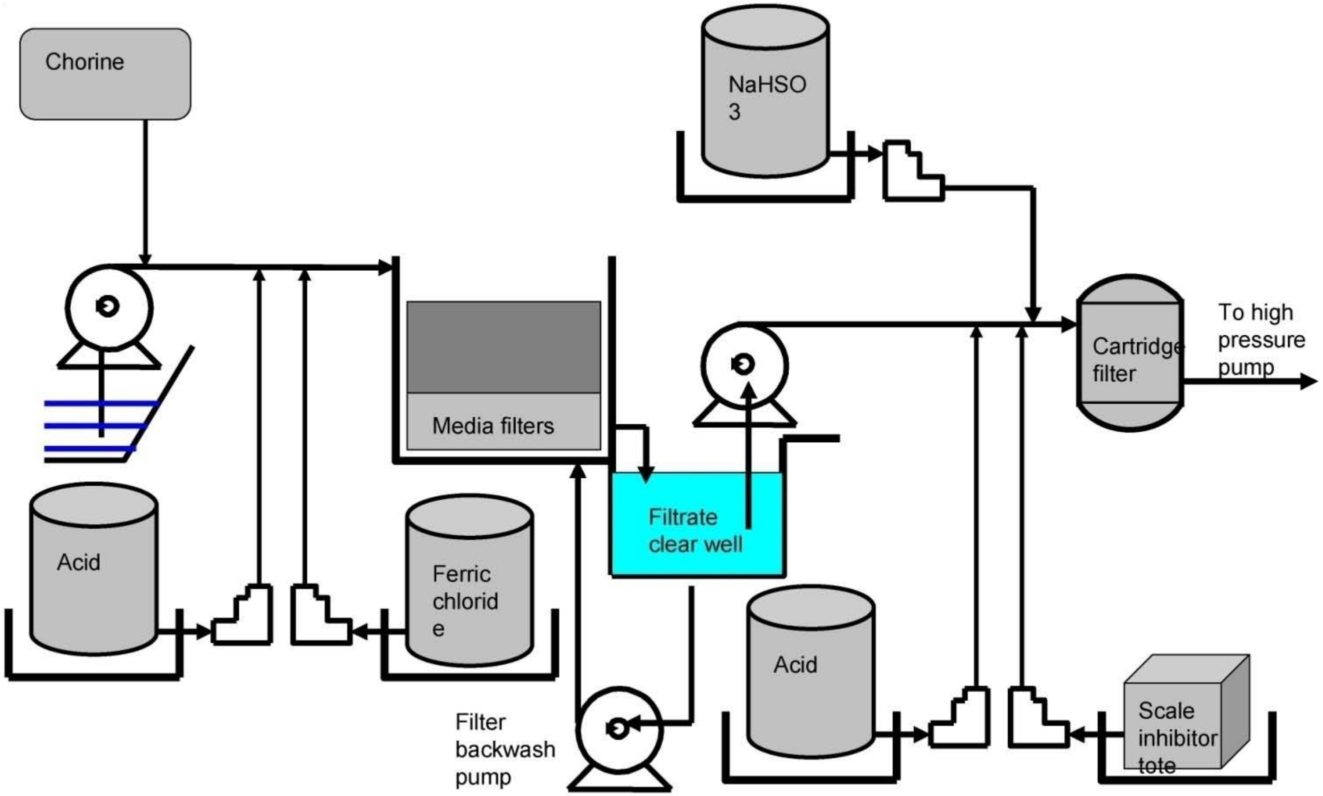
Representative Seawater RO Intake



Hydrostatic feed

Intake 10 to 15 m below surface at low tide.

Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.



Configuration of a conventional RO pretreatment system treating surface water source.

Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

Seawater pretreatment.

Disinfect with chlorine

Add ferric chloride to coagulate small particulates

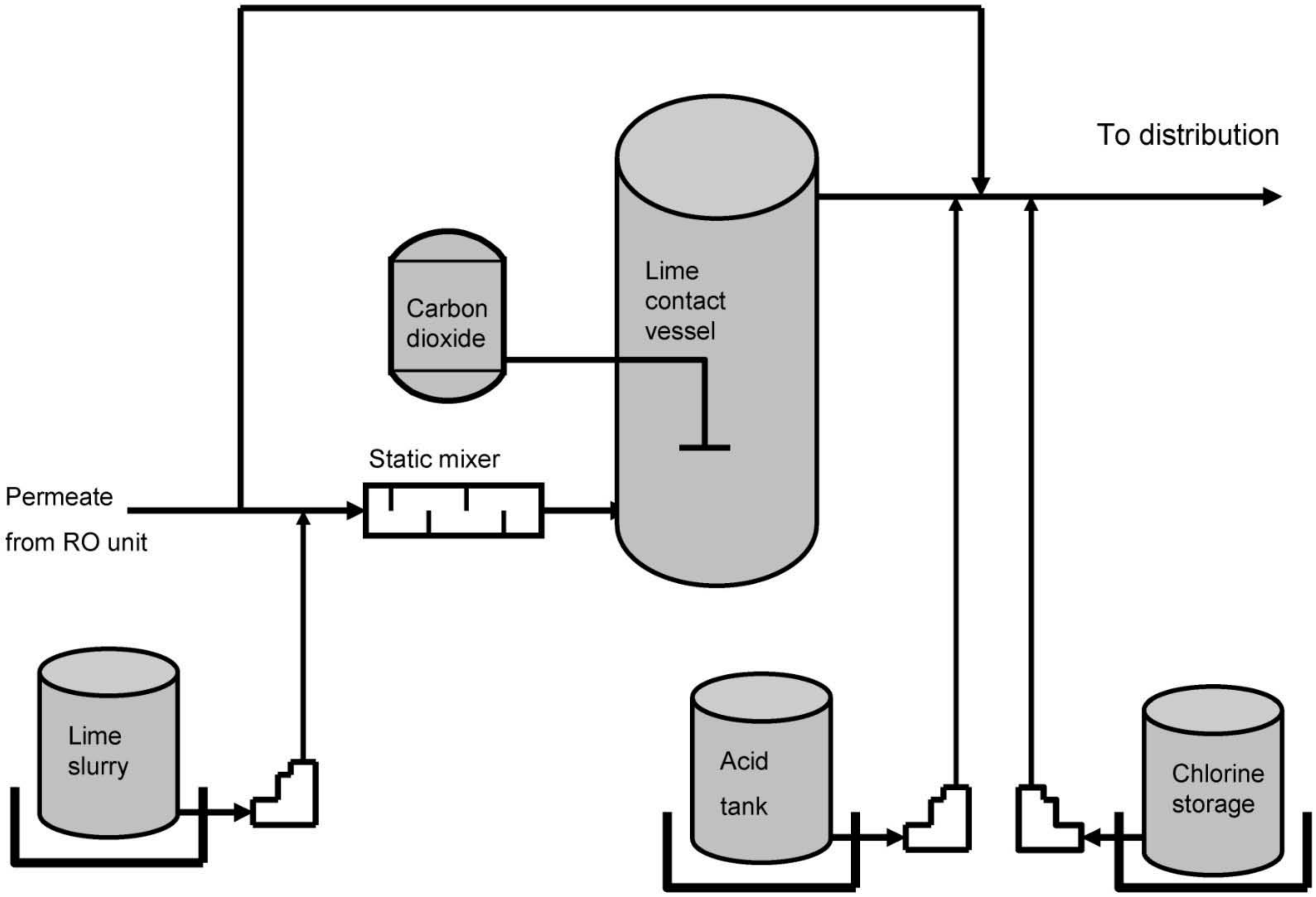
Filter, adjust pH to protect membranes, add scale inhibitor

dechlorination (by sodium bisulfate), cartridge filtration (5-15 μm porosity)

Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

Cartridge filter housing in a horizontal configuration

Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.



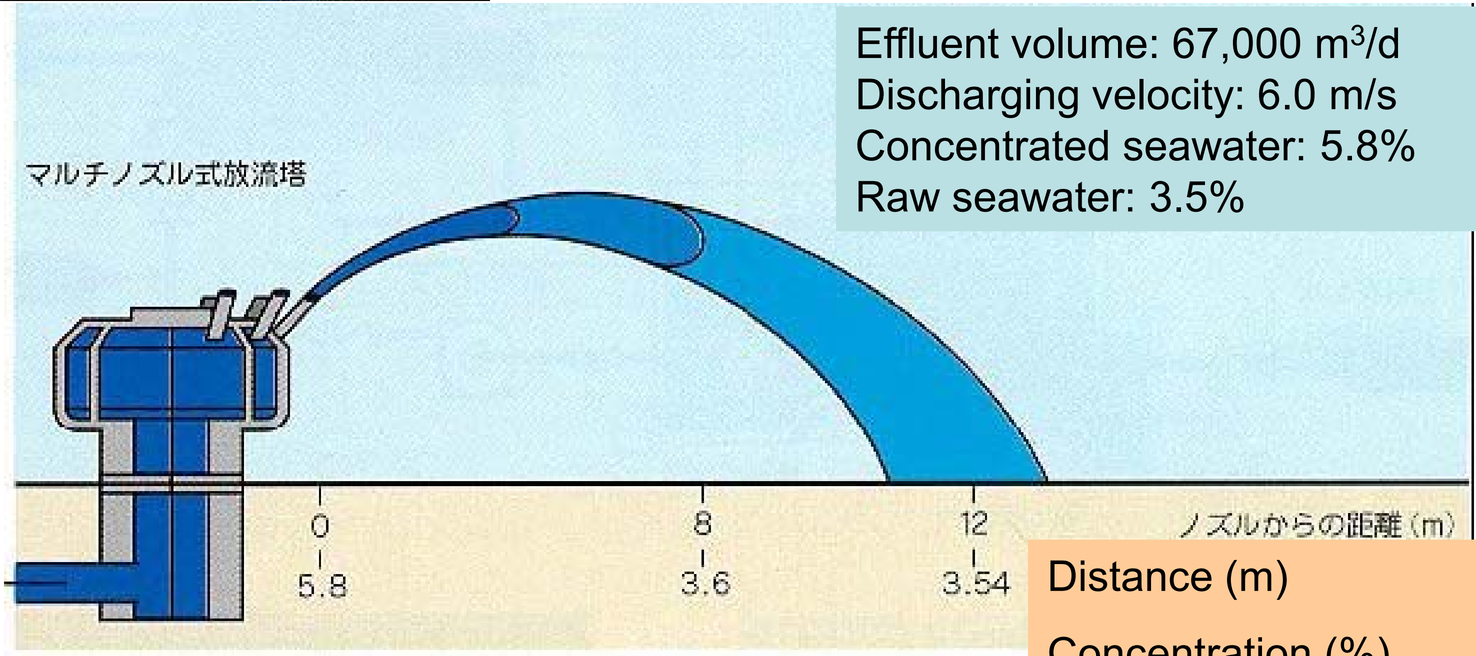
Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.

Seawater RO Post-treatment.

Add alkalinity and hardness via: CO_2+Ca(OH) → $Ca(HCO_3)_2$

Disinfect with additional chlorine, control pH

Diffuser for concentrate discharge



Effluent volume: 67,000 m^3/d
Discharging velocity: 6.0 m/s
Concentrated seawater: 5.8%
Raw seawater: 3.5%

Distance (m)

Concentration (%)

Figures from: Wilf, M., and M. Balaban. *Membrane Desalination and Membrane Filtration*. L'Aquila, Italy: European Desalination Society, 2007. Used with permission.