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Desalination Technologies for Produced Water Treatment

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

Why treat produced water?

Cost avoidance (volume reduction of disposed waste):

cost to dispose of produced water:	$1 - $5/bbl
cost to desalinate produced water:	<$0.5/bbl (not incl. transportation)

at 80% recovery, cost savings can be ~30% - 70%! **Is this realistic?**

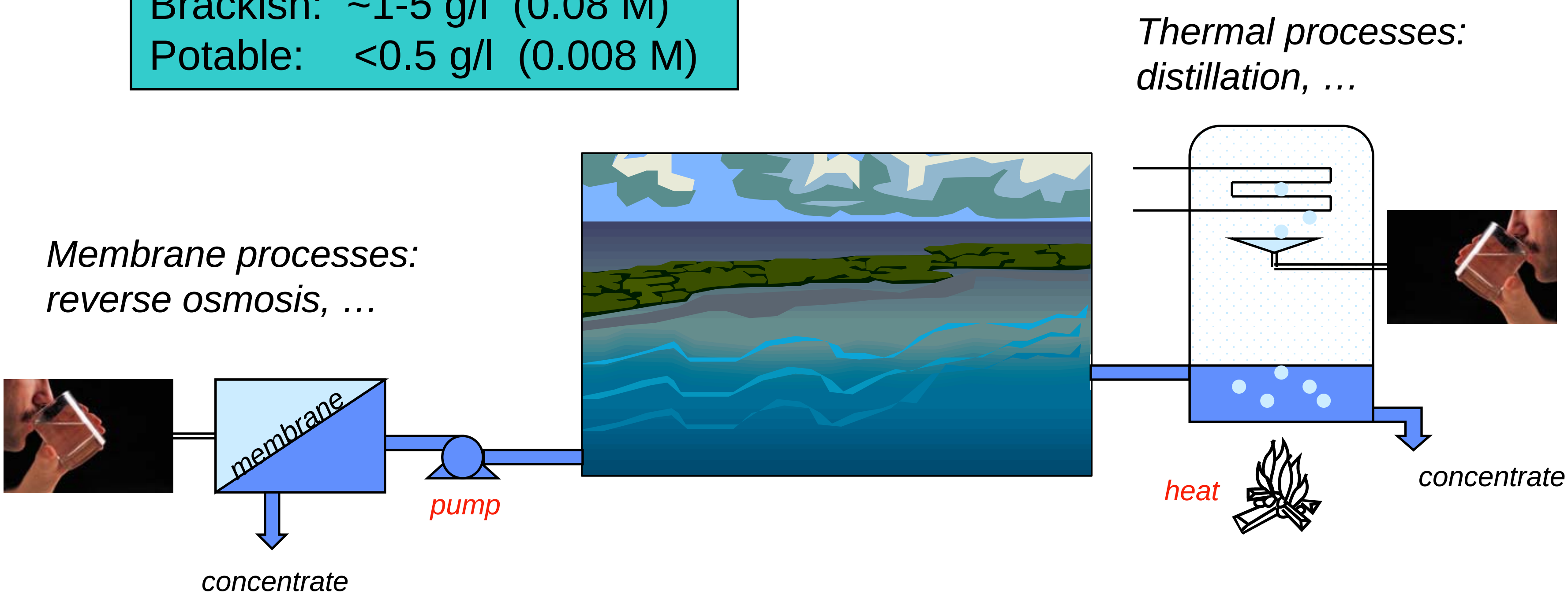
Beneficial uses of treated water:

rangeland/riparian rehabilitation
industrial process use (cooling water, biofuels)
product development (dairy, bottled water, brewery, etc.)
municipal water supply
return flow credits (e.g. Altela/Farmington)
surface reservoir storage
aquifer storage

Desalination Technologies

Salinity Levels:

Seawater: ~35 g/l (0.6 M)
Brackish: ~1-5 g/l (0.08 M)
Potable: <0.5 g/l (0.008 M)



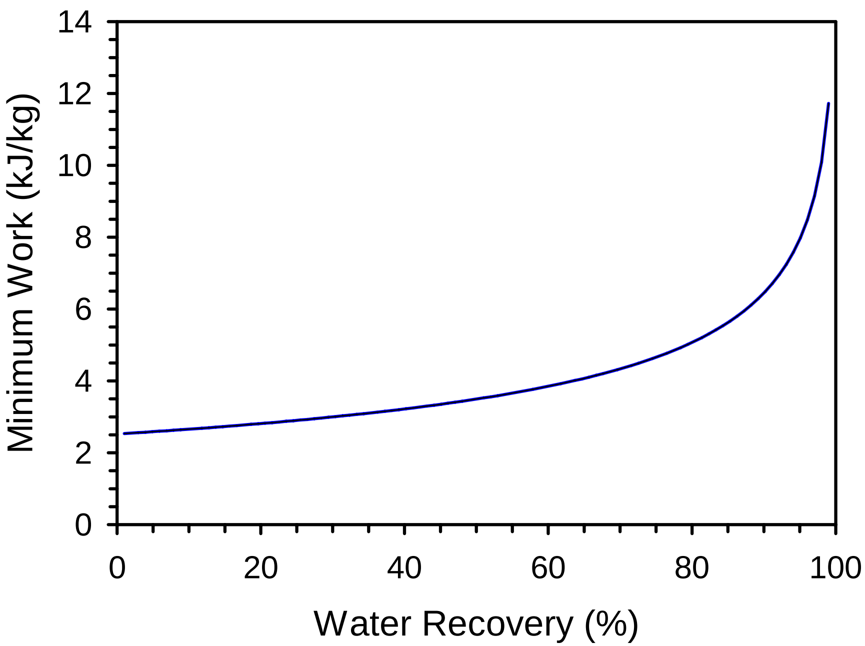
Concentrate Management and Disposal

- disposal is major environmental and economic problem for inland desal

Energy Use and Efficiency

- energy use is ~40-60% of desal water cost

Theoretical Energy Requirements for Desalting Seawater are Small…



3-7 kJ/kg water
(60 watt bulb for 1 min/kg)

… but phase change processes are energy intensive

Energy required to boil (or freeze) water:

C_p= 4 kJ kg^{-1} deg^{-1}

ΔH_{vap} = 2500 kJ kg^{-1}

ΔH_{fus}= 323 kJ kg^{-1}

Thermal processes are being replaced by membrane processes with lower energy requirements

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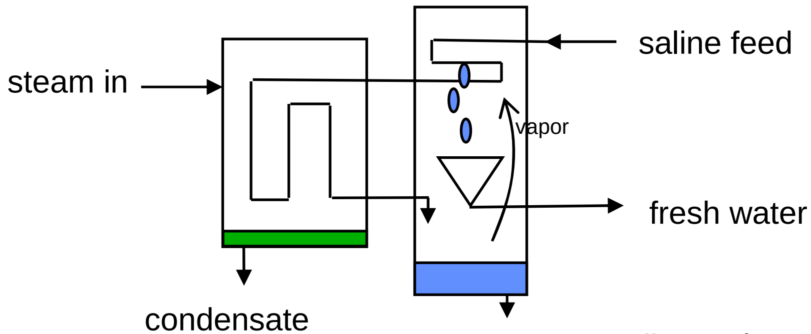
Thermal processes: phase change

Flash evaporation



Taweelah, UAE - 258 mgd

Energy required to boil (or freeze) water:

$C_p = 4\ kJ\ kg^{-1}\ deg^{-1}$

$\Delta H_{vap} = 2500\ kJ\ kg^{-1}$

$\Delta H_{fus} = 323\ kJ\ kg^{-1}$

- large amount of energy necessary for phase change
- heat recovery essential
- typical energy use ~250 kJ kg^{-1} (conc. independent)
- distillation only makes sense if energy is cheap (Middle East) and salt conc. is high (seawater)
- freezing processes have slight advantage

Note: theoretical minimum energy required to extract fresh water = 3 kJ/kg!

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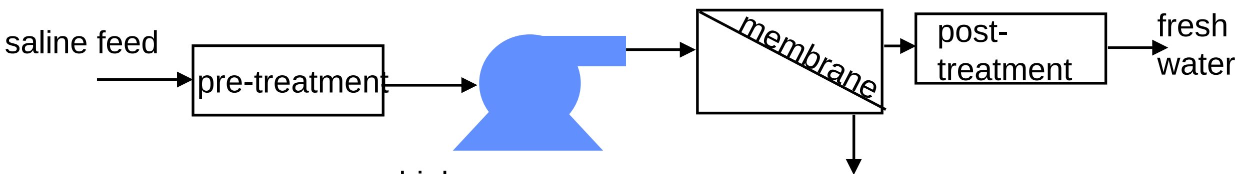
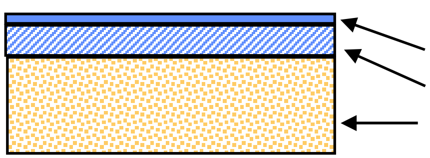
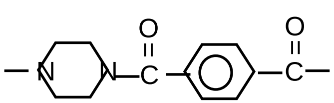
Membrane processes: reverse osmosis



Tampa Bay Water - 25 mgd

Thin film composite membrane





polyamide

- typical energy use (high pressure pump) ~ 10 – 50 kJ kg^{-1} (conc. dependent)
- energy recovery essential for seawater RO
- membranes susceptible to fouling; pre-treatment required
- polyamide membranes degraded by Cl

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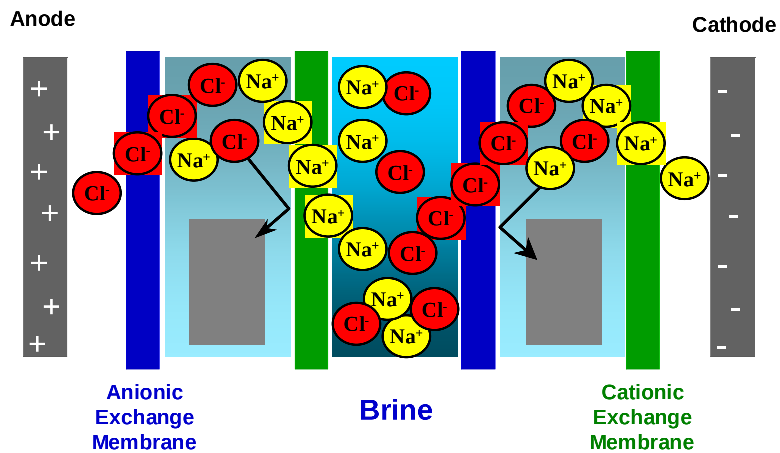
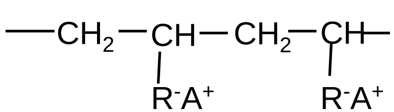
Membrane processes: electrodialysis



Sanuki Salt Manufacturing Plant, Japan

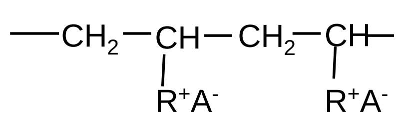
Ion exchange membranes: polyelectrolytes

cation exchange



$R = -SO_3^-$
$-COO^-$

anion exchange



$R = -NR_3^+$

- major application is in chlor-alkali process
- energy use = I^2R; ~5-10 kJ kg^{-1} (conc. dependent)
- chemical stability, electrical resistance of membrane is crucial
- selective membranes for specific ions possible

Energy Usage for Reverse Osmosis (RO), Multi-Stage Flash (MSF), and Vapor Compression (VC)

(kJ/kg fresh water)

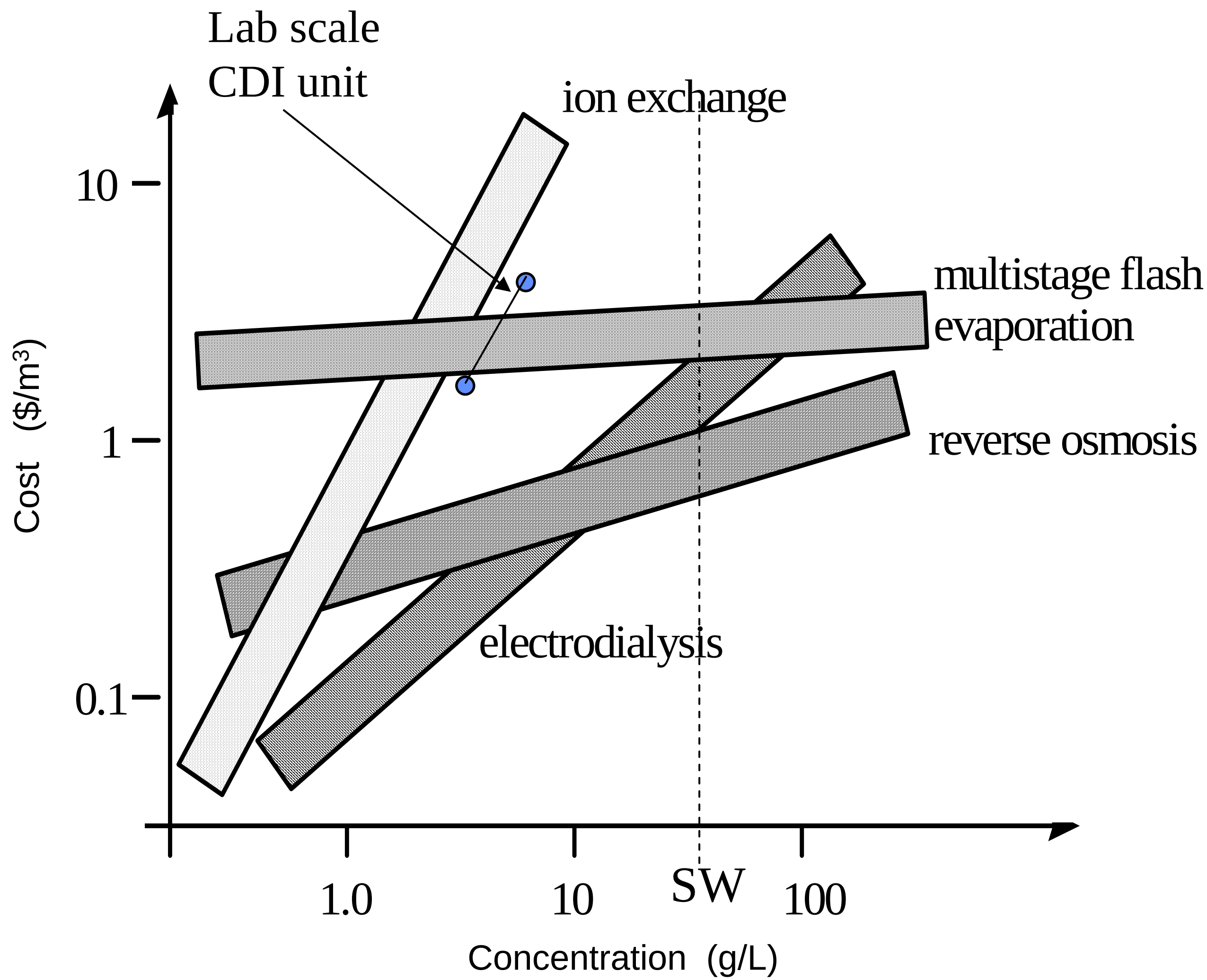
Reference	Seawater RO	MSF	VC
A	61	299	
B	15-28	95	
C	27	230	
D	23-30	290	
E	18-22 (11 brackish)	216-288	
F	11		25-43
G	15-28		29-39
H			22-29
I			14-29
J			25-36
K			26
L			37

divide by 3.6
for $kWhr/m^3$

Must account for differences in thermal and electrical energy

A. R.V. Wahlgren, Wat. Res. 35 (2001) 1.
B. L. Awerbuch, Proc. IDA World Congress on Desalination and Water Reuse, Madrid, 4 (1997)181.
C. M.A. Darwish; N.M. Al-Najem, Applied Thermal Engineering 20 (2000) 399.
D. K.S. Speigler and Y.M. El-Sayed, A Desalination Primer, Balaban Desalination Publications, Santa Maria Imbaro, Italy (1994).
E. K.E. Thomas, NREL report TP-440-22083 (1997).
F. O.K. Buros, "The ABCs of Desalting, Second ed." International Desalination Association, Topsfield, Mass, 2000.
G. L. Awerbuch, Proc. Intnl. Symposium on Desalination of Seawater with Nuclear Energy, IAEA (1997) 413.
H. H.M. Ettouney, H.T. El-Dessouky, I. Alatiqi, Chemical Engineering Progress, September 1999, 43.
I. F. Mandani, H. Ettouney, H. El-Dessouky, Desalination 128 (2000) 161.
J. F. Al-Juwayhel, H. El-Dessouky, H. Ettouney, Desalination (1997) 253.
K. S.E. Aly, Energy Conversion and Management 40 (1999) 729.
L. J.M. Veza, Desalination 101 (1995) 1.

Relative costs of desalination processes



$1/m³ = $0.16/bbl = $3.75/1000gal

Distillation

Pros:

- simple
- effective for high TDS; can achieve high recovery
- can use waste heat, solar heat, on-site gas
- can operate at low temperatures (within limits!)
- remote, off grid compatible
- few problems with fouling, scaling

Cons:

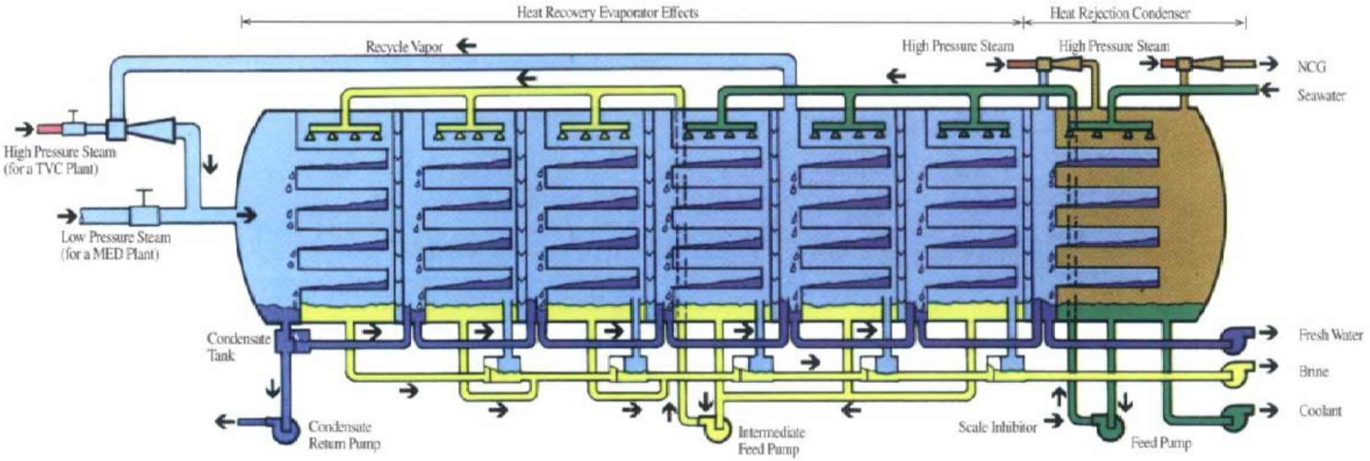
- high energy consumption
- low throughput

Configurations:

- multi-stage flash
- multiple effect
- vapor compression (thermal, mechanical)

Multiple effect distillation

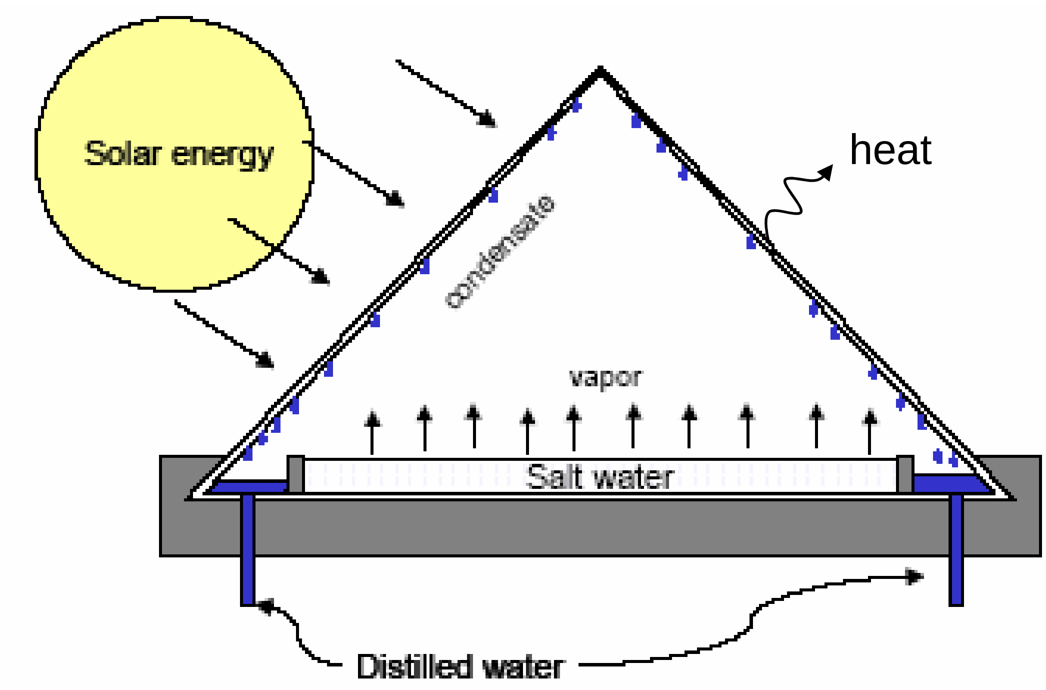
- repetitive steps of evaporation/condensation each at a lower temperature
- low grade steam input
- generally most efficient distillation method



Source: IDE Technologies, Ltd.

Low Temperature Distillation

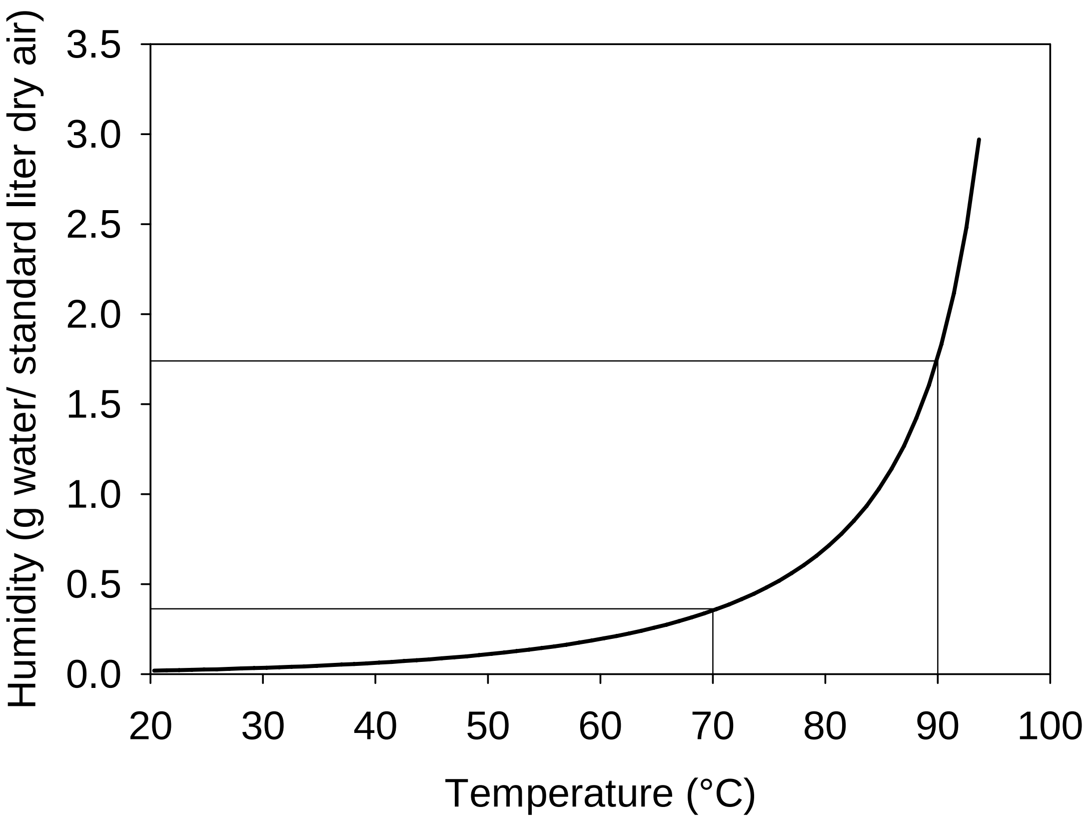
Basic solar still



- many variations
- effective use of abundant but 'low grade' solar energy
- large collection areas required for high throughput
- dissipation of ΔH_{vap} in condenser is often limiting; effective heat sink required
- high potential for small-scale use in high-sun areas; needs cheap, reliable manufacturing

Limits to Low Temperature Distillation Processes

H_2O vapor pressure or saturated water content is a sensitive function of temperature



- **low temperature processes require large collection areas or have low throughput**

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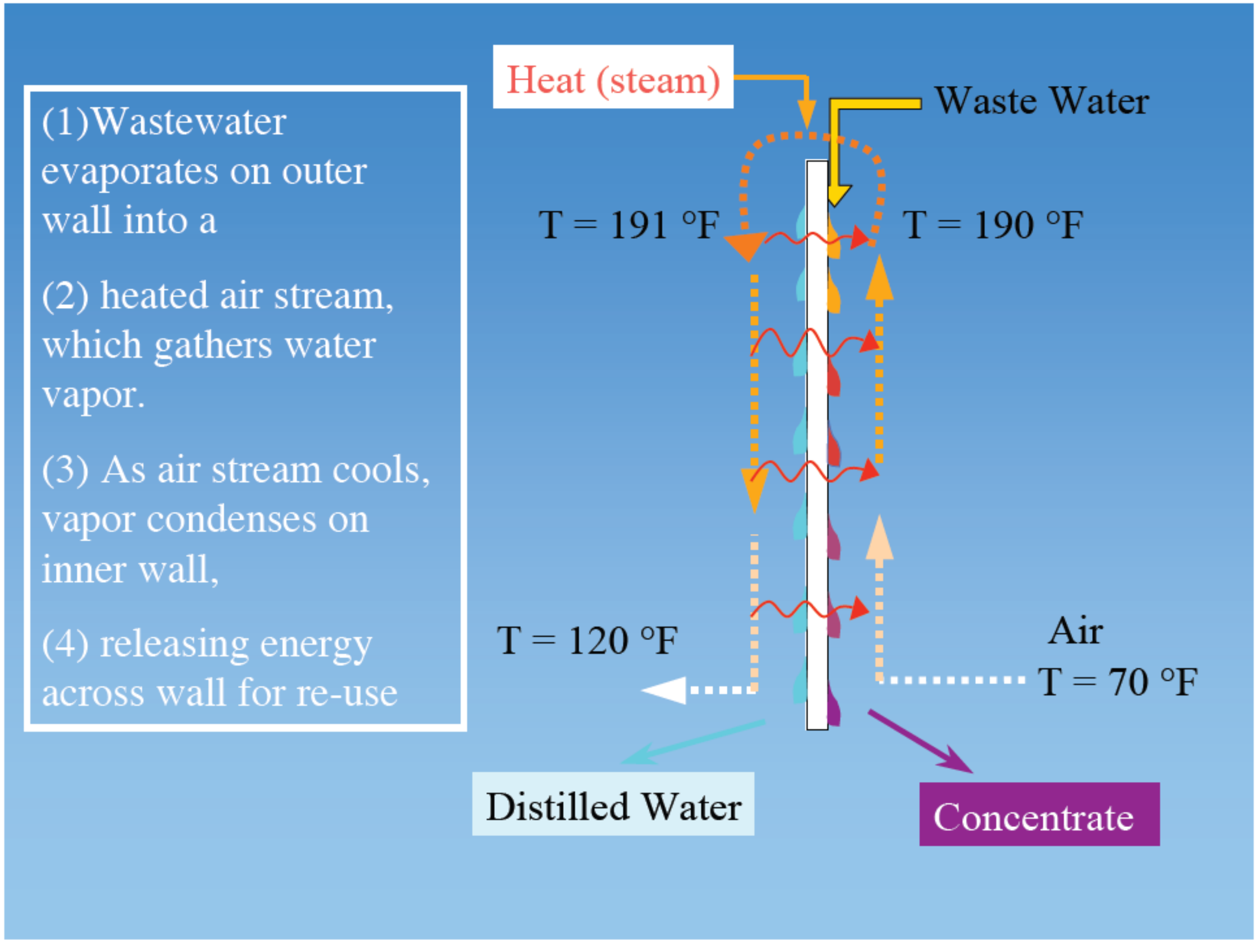
"DewVaporation" Concept

- thermal vapor compression
- developed at Arizona State Univ.



source: *L'Eau*

Characteristics of DewVaporation

source: *Altela*

- variety of heat sources are useable: e.g. gas, waste, solar
- economical *IF* heat is 'free'
- relatively low flux, throughput
- VERY pure distilled water (is this good?)
- can be made of inexpensive materials; capital costs can be low
- modular construction amenable to mobile/remote deployment
- pretreatment necessary? scaling and fouling properties unknown

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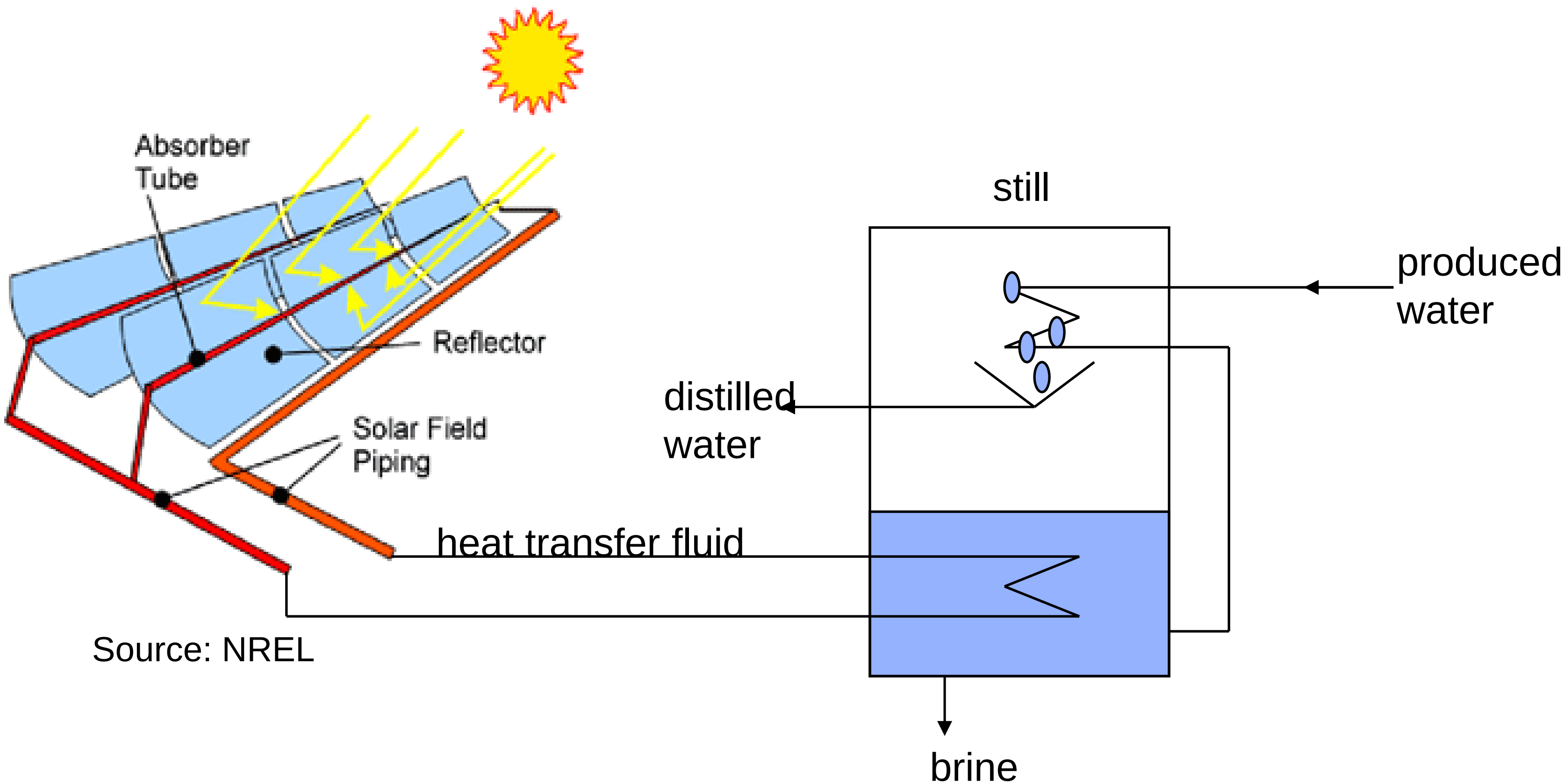
Concentrating solar distillation

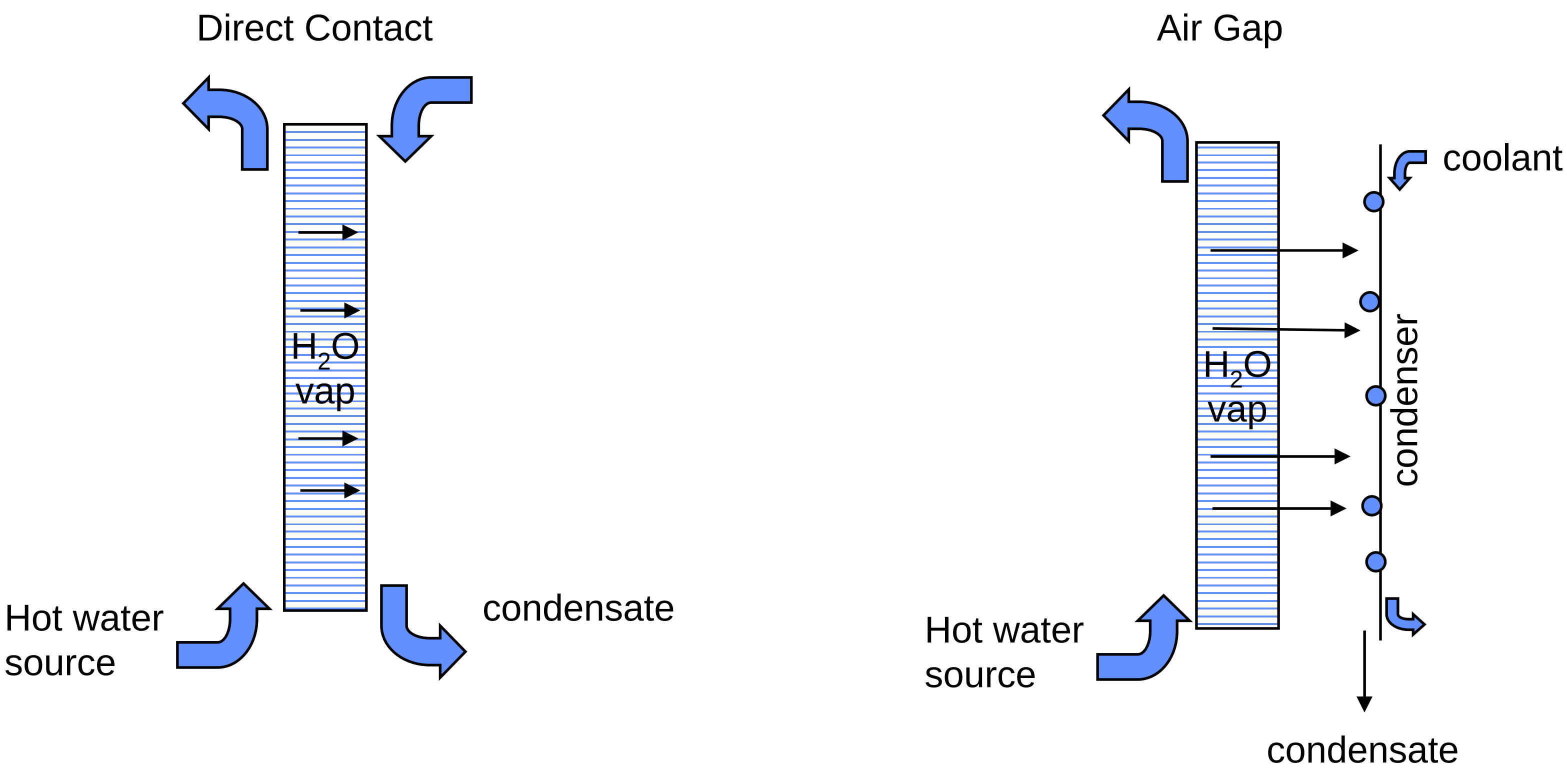
- solar powered; remote site compatible
- applicable to many distillation configurations



Source: NREL

See: http://www.nrel.gov/csp/

Membrane Distillation



- Direct contact MD vs. Air gap MD
- Up to 120 kg/m^{2}h for DCMD; 99% salt rejection
- Uses low grade/waste heat
- Small plant footprint/low capital costs

Membranes (Reverse Osmosis): pros and cons

Pros:

- mature technology; readily available
- low energy consumption
- high throughput
- high recovery for low TDS

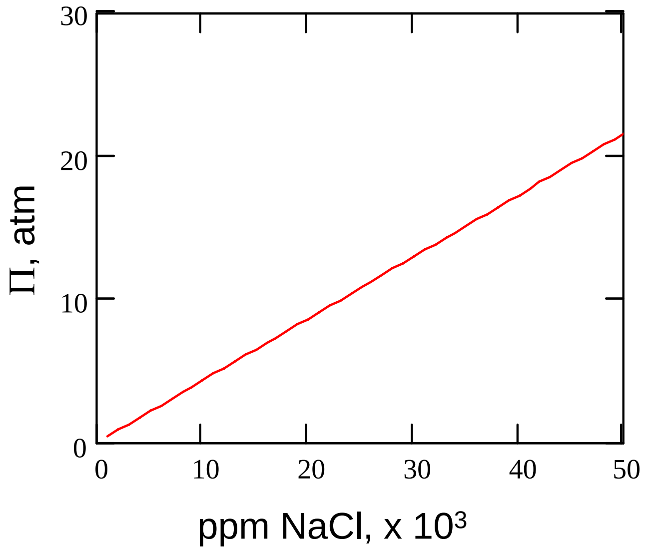
Cons:

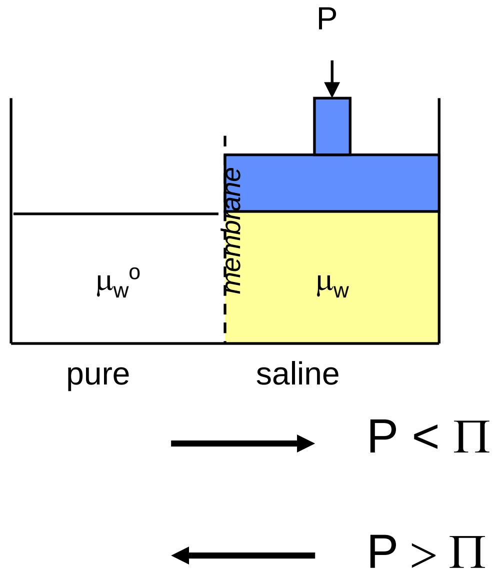
- electrical infrastructure required
- careful pretreatment required
- low recovery for high TDS
- ‘high maintenance’, skilled operator

Principles of Reverse Osmosis

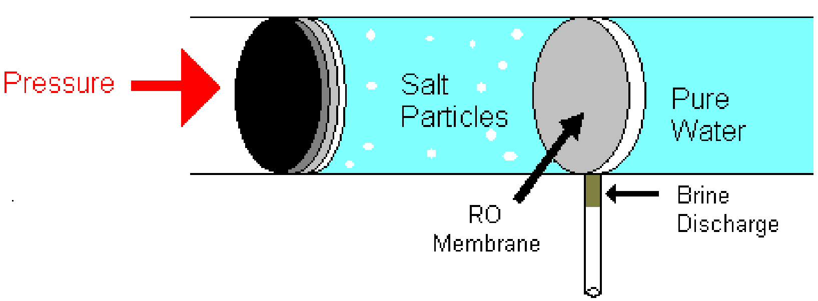
Osmotic pressure:

$$\Pi = n_s RT/V$$





Function of RO Membrane



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Typical RO installations

Commercial (GE) unit

http://www.ionics.com/technologies/ro/index.htm#

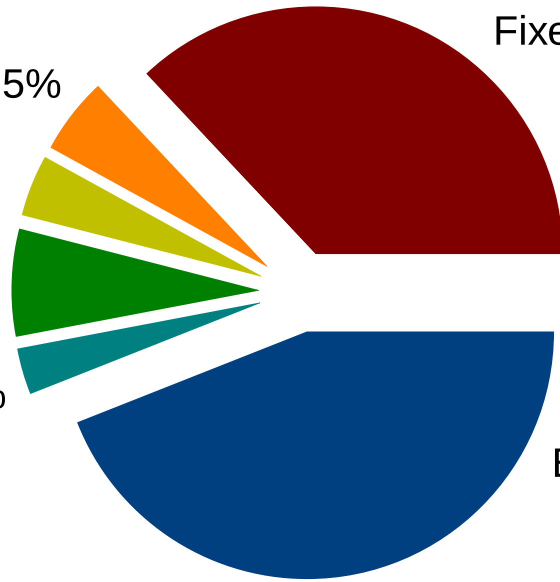
- two stage, ~2500 bbl/day

US Navy expeditionary unit

- two stage, ~2500 bbl/day

RO cost components

Seawater desalination (35,000 ppm TDS)



+ pretreatment and concentrate disposal

R. Semiat, Water International, Vol. 25, 54, (2000).

Pretreatment can be up to 30% of Total Operating Costs

K.S. Speigler and Y.M. El-Sayed, A Desalination Primer, Balaban Desalination Publications, Santa Maria Imbaro, Italy (1994).

Pretreatment for Reverse Osmosis

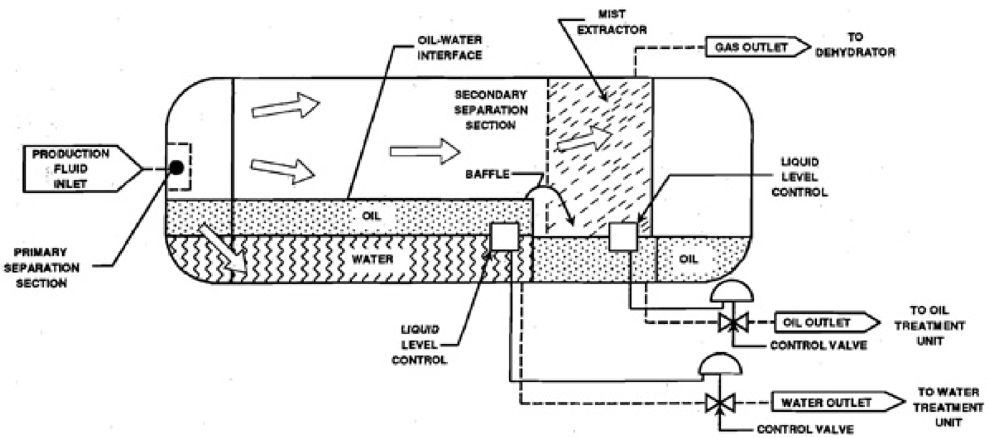
- membranes are prone to fouling and scaling
- leads to lowered flux, high energy consumption, shorter life

Culprits:

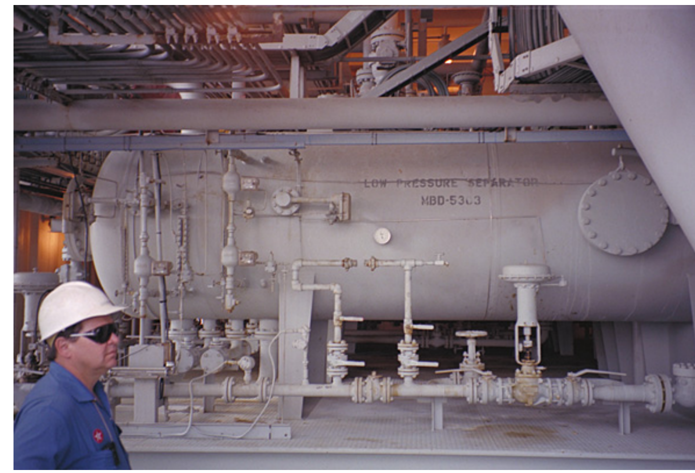
oil / grease / dissolved organics
suspended and colloidal solids
biologically active materials (bacteria and food)
sparingly soluble minerals (sulfates, carbonates, silica)

Pretreatment: oil/water separation

Three phase separator



Source: EPA



Source: J. Veil, ANL

- oil stream may contain some water
- water stream may contain some oil
- *treatment of the produced water usually requires removing emulsified or dissolved oil*

Pretreatment: solids and oil droplets

- solids usually CBM coal fines

Technology Removal Capacity by Particle Size (Units in Microns)	
API gravity separator	150
Corrugated plate separator	40
Induced gas flotation without chemical addition	25
Induced gas flotation with chemical addition	3-5
Hydrocyclone	10-15
Mesh coalescer	5
Media filter	5
Centrifuge	2
Membrane filter	0.01

Source: Frankiewicz (2001)

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Pretreatment: dissolved and dispersed oil/grease/organics

Solvent extraction:

- macroporous polymer media
- high capacity for BTEX, PAH, <C_{20}
- not as effective for >C_{20}
- steam regenerable

Adsorption:

Organoclays

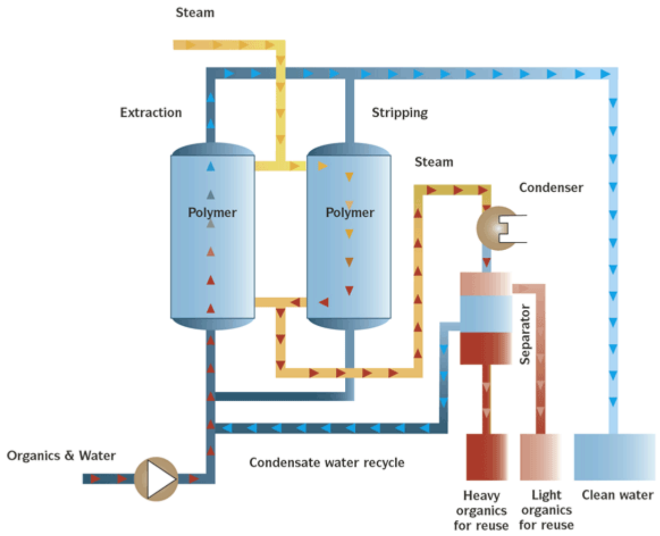
- surfactant modified clay mineral; high capacity ~1g/g, including droplets
- cannot be regenerated (?)

Zeolites

- surfactant modified nanoporous mineral; good for low MW (BTEX)

Activated Carbon

- nanoporous carbon; high capacity for low MW
- often used as polishing stage with organoclay
- can be regenerated



Source: VWS MPP Systems B.V.

Source: J. Veil, ANL

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Pretreatment: sparingly soluble minerals

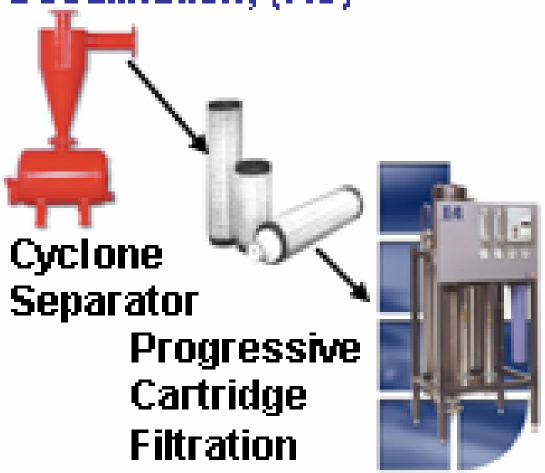
Chemical additions

- anti-scalants – can work to 3 x supersaturation
- lime softening – CaOH added to precipitate $CaCO_3$
- $Fe(OH)_3$ precipitation of silica
- pH adjustment for solubility, corrosion control

Desalinating Coal Bed Natural Gas Brackish Produced Water

Problem: Handling of Produced Water from These Wells, a Severe Environmental Problem
Approach: Turn Environmental Problem into Asset, Treat Use Produced Water Beneficially Where Possible

Removal of Coal Fines, Iron, Organics Precede Desalination, (RO)



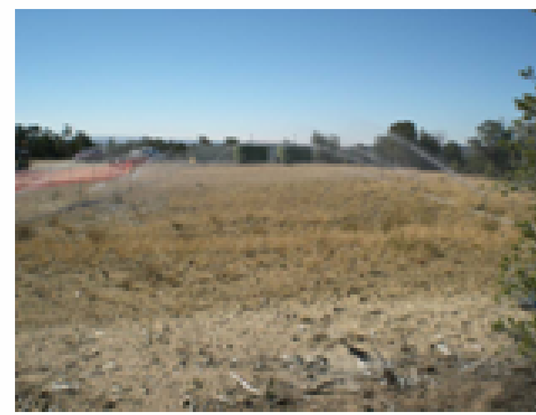
Cyclone Separator

Progressive Cartridge Filtration

Ultrafiltration, (lastly) Reverse Osmosis

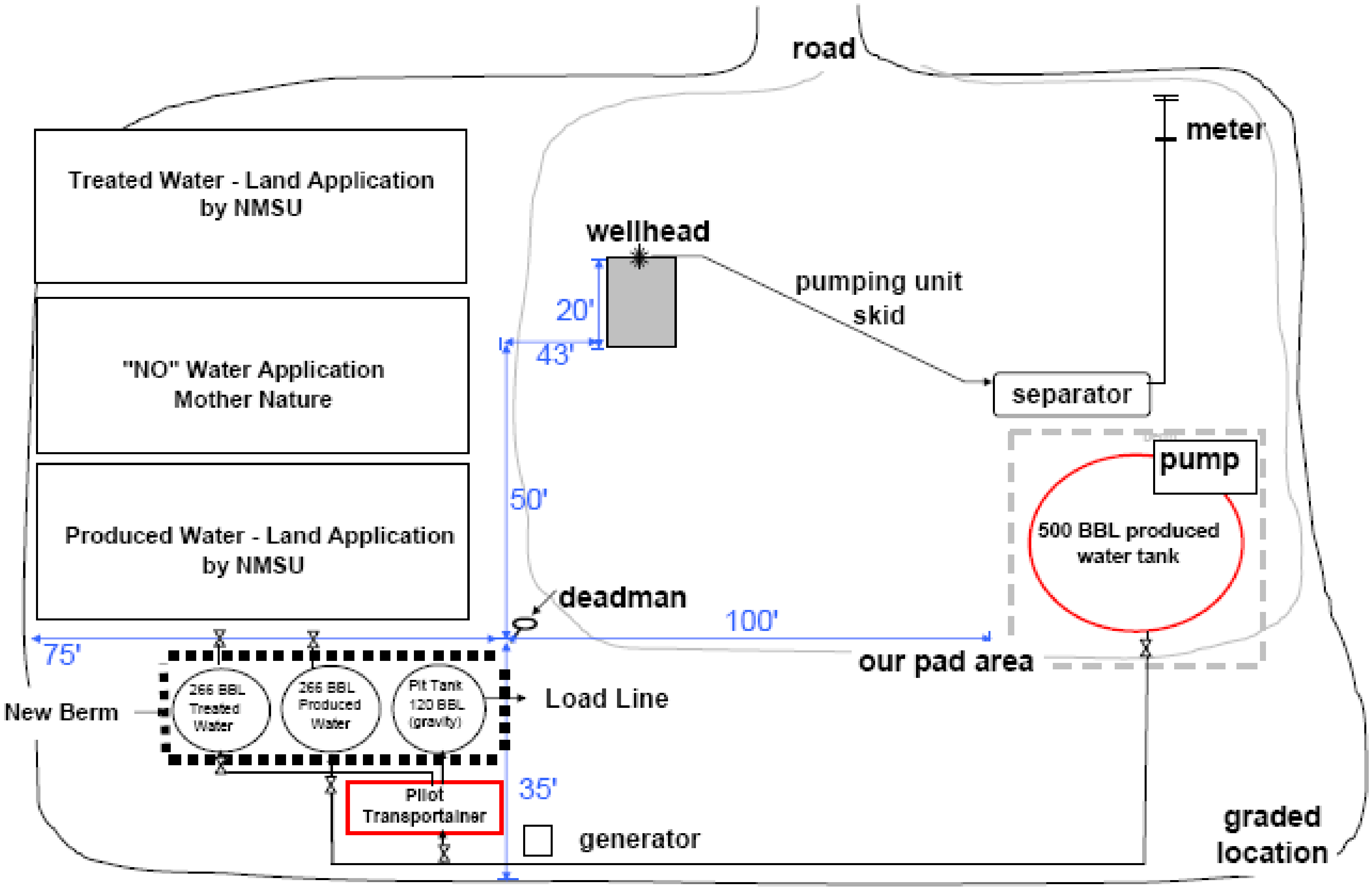
Processing Produced Water, in Old Arsenic Project Transportainer

Use Treated, Untreated Water in Revegetation Study on the ConocoPhillips Site



- Treat Produced Water from Coal Bed Natural Gas Wells Economically as Possible
- Work with ConocoPhillips, New Mexico State University and US Department of Agriculture on Repair of Disturbed Vegetation and of Impaired Riparian Areas

Pad Site 32-8 237A schematic



ConocoPhillips Four Corners Site for Pilot Desalination and Rangeland Improvement

Treated, Untreated Water, Concentrate Tanks (Left), Grasses to be Watered on Right

Water Treatment Within Recording Unit

Separator, Produced Water Tank from Well, Shower, Flush Toilet and Sauna (in blue building)

Take Home:

- technologies exist to adequately treat produced water

- distillation and reverse osmosis are known quantities with pros and cons; many alternative methods not proven, some have promise

- treatment costs are not well established, but may be competitive with waste disposal

- cost barriers likely to be collection, transportation, distribution

- beneficial uses can recover value of ‘lost resource’

See the Produced Water Management Information System:
web.evs.anl.gov/pwmis/

(maintained by Argonne National Labs, J. Veil)

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