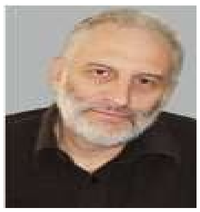
Development of a Forward Osmosis Desalination Technique



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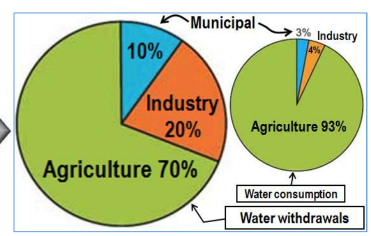
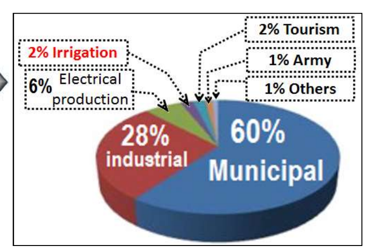
Agricultural market for desalinated water

1. **Agriculture is the largest consumer of fresh water**



2. **Only 2% of world desalination capacity is using for agricultural needs, though.**



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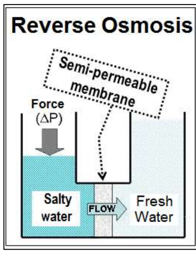
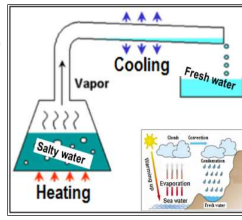
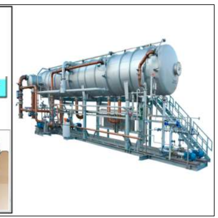
Currently commercially accepted desalination methods: reverse osmosis (RO) and distillation



Distillation

RO





- Comparable water quality for both technologies
- RO offers rather better price

RO is now a benchmark for desalination industry

Nowadays RO-plants produce twice more water than distillation-type plants

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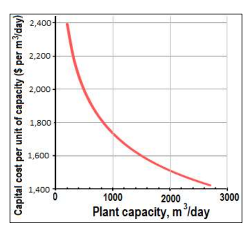
The limited agricultural use of desalinated water suggests that currently the technologies don't meet the farming requirements. Why is it the case?

- Agriculture needs substantially cheap water
  - ✓ Farming cannot afford the price, which is reasonable for other consumers

- Farming favors small desalination plants:
  - ✓ The consumption is distributed over huge areas
  - ✓ The extensive distribution pipelines are expensive and require costly maintenance.

Only large scale RO facilities may offer a rather passable fresh water cost



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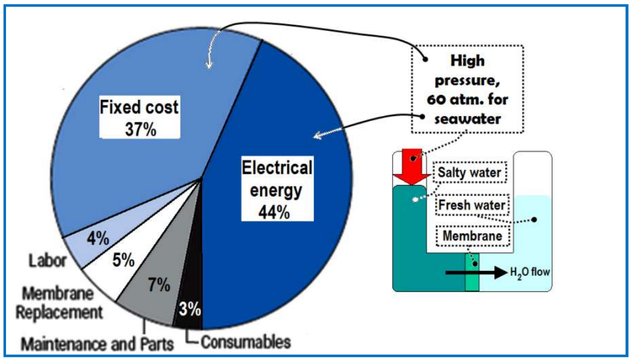
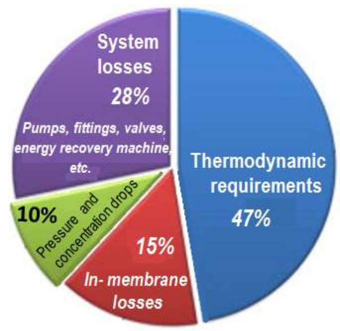
Two major components of the RO desalination cost: *Fixed cost *Energy cost





- Energy: the RO plant efficiency hardly may be markedly improved being ~50% of the thermodynamic minimum
- Fixed cost: the application of high pressure suggests the high cost of the equipment

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The price of RO – desalination hardly can be substantially diminished

The problematic point of RO is not the specific quantity of energy for the process but its cost.

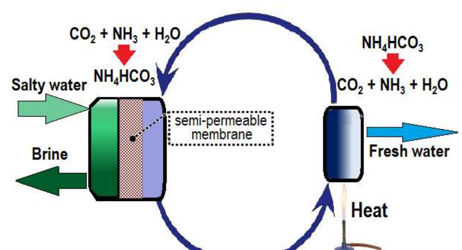
The alternative - forward osmosis (FO) desalination process

First step - exchanging salts into the saline water for an easily removable material (draw solute, DS)

Second step – decomposing DS, renmoving the decomposition products and collecting fresh water

Third step – collecting the decomposition products and DS regeneration

- The major advantage of FO desalination is not the energy saving but employing cheap type of energy, mostly low temperature (< 70ºC) heat energy.
- The additional benefit - the process takes place at the ambient pressure, so the unit don't require the implementation of expensive components.



Korea Institute of Machinery and Materials, Daejeon, Korea
http://chenected.aiche.org/tools-techniques/forward-osmosis-pilot-plant-for-seawater-desalination/

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Currently the most developed are FO desalination units with inorganic thermolytic salts like ammonium bicarbonate

Up to now, FO – based desalination is still not industrially accepted

The problematic points:

- DS decomposition products are too soluble in water, and it is difficult to separate them obtaining a potable quality fresh water
- The recombination reaction of the solute (solute recycling) is slow.
- Thermolytic DS materials markedly diffuse back through the membrane resulting in environmental pollution and the DS losses.

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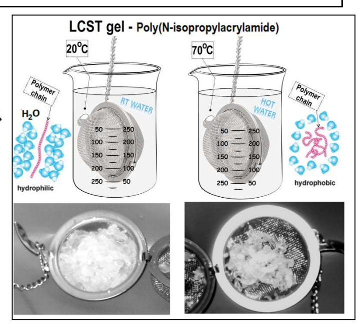
LCST gels are promising draw materials for FO desalination.

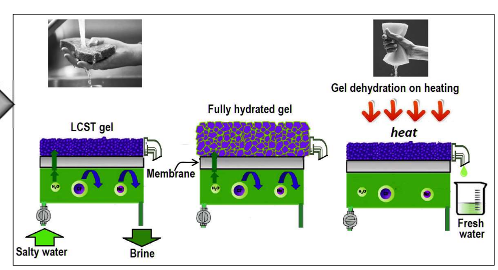
LCST gels are cross-linked polymer materials

- The gels are hydrophilic below critical temperature T_c absorbing water, and turning hydrophobic over T_c squeezing out the absorbed water.
- T_c is between 20°C and 90°C for most of the LCST gels depending on the structure of the polymer chains.



Regarding commonly accepted FO desalination unit design with LCST-gel draw material:

- The unit comprised of the horizontally laid semi-permeable membrane with a common for FO units feed water section
- The LCST gel particles are piled on the membrane in the corresponding section of the FO unit being in direct contact with the membrane.
- At room temperature, water is driven through the membrane by osmotic pressure and is absorbing by the gel.
- On full gel hydration, the feed stream is stopped, the gel is heated up over T_c , and the absorbed fresh water is squeezed out of the gel.



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The assessment of the reported FO- desalination units with LCST – gel draw material.

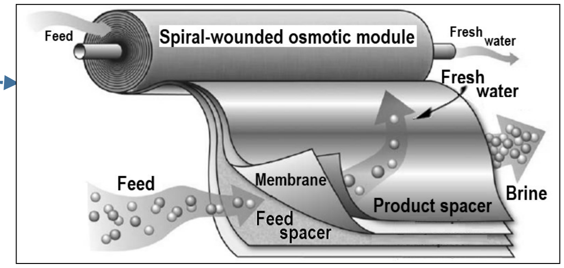
Advantages:

LCST – gel draw material solves a set of problems of FO – desalination process

- High fresh water quality is easily attainable.
- A complete recycling of the draw material is simply realizable by gel cooling.
- Draw material losses and environmental pollution are negligible.

Problematic aspects:

- Water flow rates in the unit with LCST-gel draw material are substantially below water flow rates in the FO units with common thermolytic salts.
- Large LCST - gel volume changes render the accepted design of osmotic units to be quite challenging.



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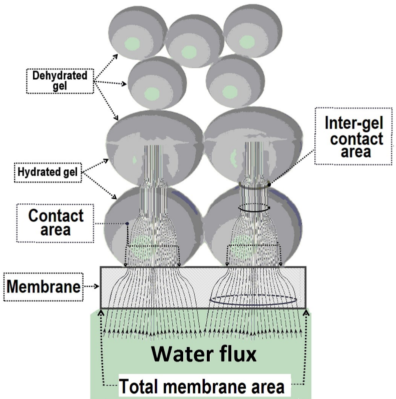
The major source of the problems with gel draw materials is the direct gel attachment to the semipermeable membrane

- The membrane/gel direct contact increases internal concentration pressure (ICP) of the osmotic process thus diminishing the effective osmotic pressure.
- The membrane/gel contact area is efficient for water transport, and this area is substantially smaller than the apparent membrane area
- Besides, the presence of the inter-gel pile bottle-necks also hinders water diffusion



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Solving the problem of a low water flux

A compound FO desalination process with two draw materials avoids membrane-gel contacts and inter-gel pile contacts substituting them with membrane – liquid and gel-liquid contacts.

The approach:
- **Offers a substantial enhancement of water flux**
- **Paves the way for implementation an advantageous spiral-wounded osmotic module design**

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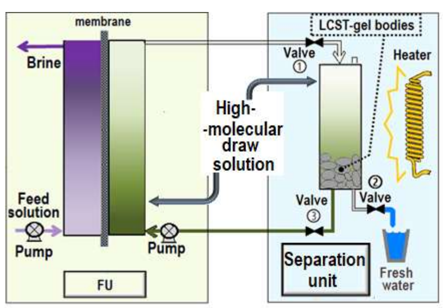
The compound FO desalination plant design

The plant comprises of two interconnected units:
- Forward osmosis unit (FU)
- Separation unit

The pumps maintain the flux of a feed solution in FU and the draw solution in the corresponding FU and separation unit hydraulic circuits.
- The draw solution is the solution of a high –molecular compound; the preferable draw solutes are polyelectrolytes

The separation unit contains LCST gel body
- The separation unit is equipped with a heat source (up to 70ºC)



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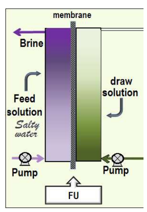
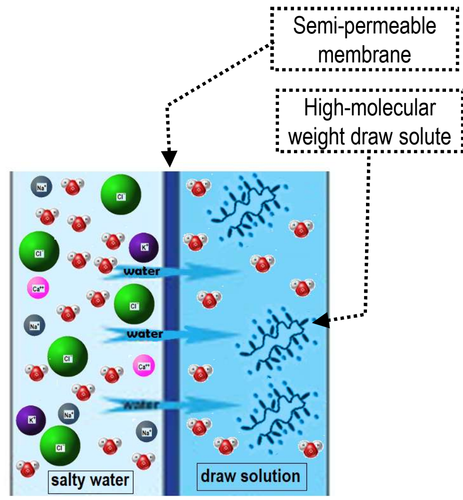
How it works I - the FO unit

- FO unit operates in a common way so that water is moving through a semi - permeable membrane from salty water (feed solution) toward draw solution being driven by the difference in osmolality of feed solution and draw solution.
- Draw solute has adequately large molecules (over 10^4 D)
  a. This is a clue issue for the separation process
  b. It offers a negligible backflow of the draw solute
- Draw solutes of choice are polyelectrolytes; this helps t**o retain a rather high osmolality of the draw solution maintaining high molecular weight of the draw solute**





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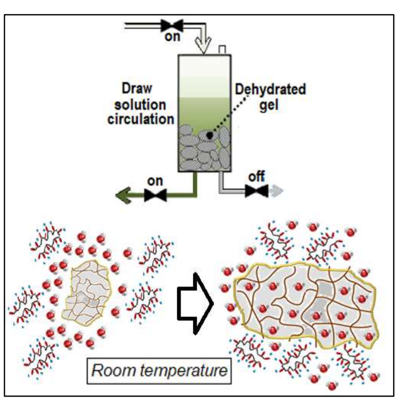
How it works II – the separation unit

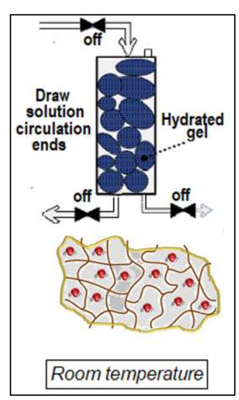
The first (starting) stage

- The draw solution is passing through the separation unit
- The dehydrated gel starts to absorb water
- Large draw solute molecules are excluded; they cannot penetrate inside the gel net being too large



The second stage

- The draw solution flow is stopped
- The separation unit contains only fully hydrated gel body



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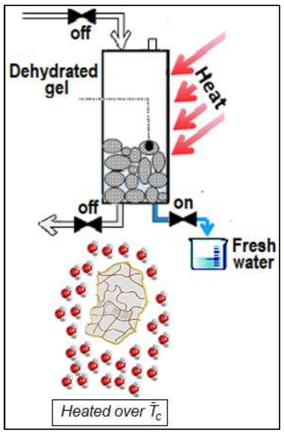
How it works II – the separation unit

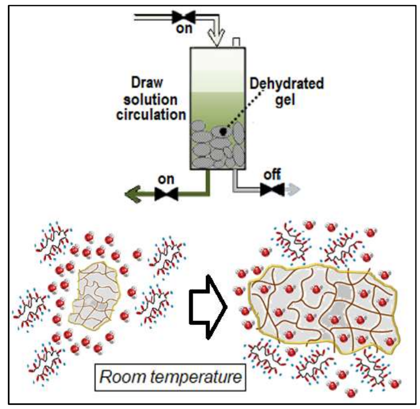
The third (water collecting) stage

- The hydrated gel is heated up to the temperature above T_c
- The gel squeezes out water, the fresh water is collecting
- The gel is recycled



The fourth stage – a new desalination cycle starts

- The gel is cooling down to the room temperature
- The draw solution is passing through the separation unit
- The recycled gel starts to absorb water
- Large draw solute molecules are excluded, etc.



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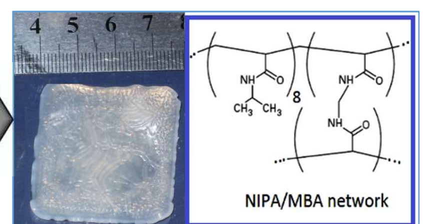
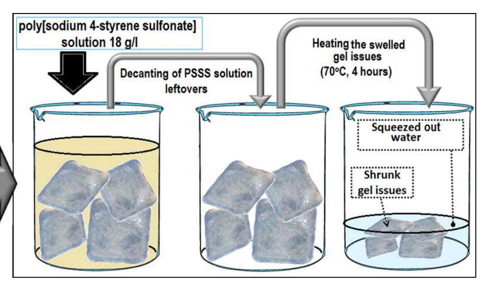
The feasibility of the LCST – gel based separation unit

- The LCST gel with T_c ~37°C (PNIPAM) was prepared by crosslinking of N-isopropyl acrylamide (NIPAM) by methylenebisacrylamide (MBA)
- On preparation, the gel passed several cycles of dehydration at 70°C followed by the hydration in deionized water at room temperature.
- The gel absorption capacity (against pure water) ~ 210% (±6%)



5 mm thick, the crosslinking degree ~ 12.5%.

- **The gel was immersed in 18 g/L poly[sodium 4- styrene sulfonate] (PSSS) solution, mv. 10^6 D**
- **The solution was decanted after overnight stay**
- **The swelled up gel was heated in the oven at 70°C for 4 h**
- **The exuded water was collected and TDS was determined.**
- **The gel capacity (against PSSS solution) ~125% (±6%)**
- **PSSS molecules were completely excluded from the gel, TDS of the exuded water was below 0.01 g/l.**



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The advantageous features of the compound FO desalination plant

- **Cheap design - operation at ambient pressures and low temperatures**
- **Consumes cheap heat energy, heat temperature below 50°C – 70°C**
  - ✓This may be waist industrial heat of solar low-temperature heating
- **No water cost dependence on the plant capacity, small plants are economical.**
- **Environmentally friendly operation, the draw solute leakage is negligible.**
- **No professional staff is required for operation and service**

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Gel peeling off on hydration/dehydration