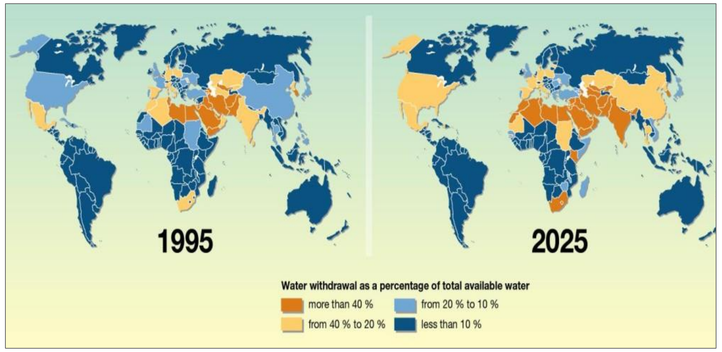
THE POTENTIAL OF CARBON NANOTUBES IN WATER DESALINATION

Brian Njihia (bnn10@pitt.edu), Ben Jarmusz (bmj32@pitt.edu)

The Threat of Water Scarcity

Water scarcity is defined as the physical shortage of water or the failure of local institutions to ensure a regular supply of fresh water due to inadequate infrastructure. Currently, about two-thirds of the world's population currently resides in areas that experience water scarcity for at least one month a year. Based on current trends, fresh water demand will exceed supply by 40% by the year 2030 leaving millions in danger if not the issue is not addressed.



Current Desalination Processes

Thermal Distillation:

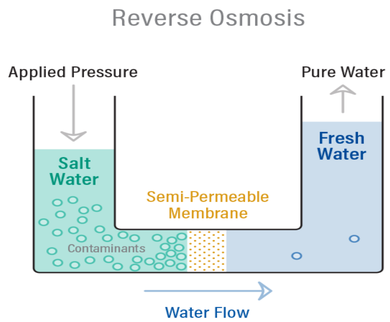
Thermal desalination is one of the oldest and basic forms of distillation. It involves heating the water to its boiling point and cooling the water vapor that forms. Once the vapor is cooled, it condenses and collects in a separate container, leaving behind the salt and other minerals. Although this method is simple, it is the most energy intensive.

Electrical desalination:

This method utilizes an electric current that is sent across a permeable membrane. Because most salts dissolved in water are either positively or negatively charged ions, these ions migrate towards the opposite poles of the electrode, leaving behind fresh water. The main problem with this method is that the energy requirement is based upon the initial concentration of ions in the water. Unfortunately, the concentration of salt and other ions in seawater is too high to make electrodialysis a viable option for desalination, as it would be too energy intensive.

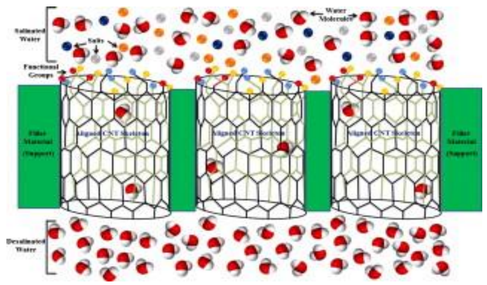
Reverse Osmosis:

During reverse osmosis, pressure is applied to the salt water solution, which is forced through a semipermeable membrane that filters out the contaminants, yielding fresh water. Compared to thermal distillation, the energy needed to produce the pressure used during the process is fairly low. On average, reverse osmosis is three times more efficient than thermal distillation in terms of energy usage.



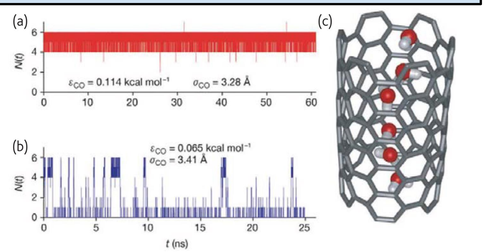
Chemical Properties of Carbon Nanotubes

- Hold promise in areas such as ion exclusion for desalination and demineralization
- Based on molecular dynamics simulations, the filtration of sodium, potassium, and chlorine ions can be achieved using CNTs with a diameter of 0.4 nm.
- Achieved by increasing the energy required for the ion to pass through the nanotube.
- Example: with 0.4 nm diameter CNT, ion must shed portion of hydration shell to pass through which requires 120 KJ/mole (kilojoules/mole); decreases to 5 KJ/mole when diameter increases above 1 nm
- Can be decorated with positive/negative charges to filter out specific ions and control their flow
- Modifications can be made to CNTs to control water transport
- Most important modification occurs at ends of the nanotube where efficient flow is established
- Involves oxidation step to remove fullerene caps and produces carboxylic groups
- Effects can be localized using voltage
- When charged, organic dyes can be used to control transport and allow for smoother, more efficient flux.



Physical Properties of Carbon Nanotubes

- Can be visualized as one dimensional graphene sheets rolled into a cylinder with a diameter on the nanoscale.
- Water is able to travel through the nanotubes in an almost frictionless manner.
- This trait can be attributed to weak interactions between walls of the CNT and water molecules.
- Water enters the CNT within several picoseconds and travels in a single-line configuration.



- Water in CNT is in thermodynamic equilibrium with water outside CNT.
- Water in CNT obtains lower free energy giving the nanotube almost biological level water transport efficiency.

Studies in Support of CNTs

- *(2010) Department of Environmental Engineering, Tehran University*
- CNTs have higher flux, higher performance, less fouling, less required cleaning, higher thermal stability, higher consistency, and lower energy requirement than conventional polymeric membranes
- Can withstand applied pressure giving it increased mechanical stability
- Able to disinfect and remove biological contaminants by piercing cell membrane integrity in viruses and bacteria

Limitations

- CNTs are difficult to produce in the large quantities needed for a CNT based desalination plant.
- Varying diameter sizes presents a tradeoff between the degree of infiltration and the rate of water transport through the nanotube.
- Example: increasing diameter from 0.32 to 0.75 nm decreases salt rejection by 42% but increases flow rate by over 300%.

Salt rejection efficiencies and flow rates of the vertically aligned CNT membranes based on molecular dynamic simulation [a][4]

Rolled up vector	Inner diameter (nm)	Salt rejection (%)	Flow rate (LMH) [b]	Enhancement [c]
(5,5)	0.32	100	66.7	2.42
(6,6)	0.49	100	112.5	4.21
(7,7)	0.59	95	175.0	6.39
(8,8)	0.75	58	270.8	9.76

- Efficiency of membrane permeability of CNT susceptible to biofouling. This damages the structure and adds friction increasing energy required to pass water through.
- Increased energy results in higher operating costs.

Sustainability

Economic:

Electricity alone makes up 41% of the overall cost to create the pressure necessary to force salt water through the semi-permeable membranes used in reverse osmosis. Therefore, the more efficient the membrane, the less energy is required to push the water through. Using a standard polymeric membrane requires 3 to 5.5 kWh/m^3, but using a CNT membrane requires closer to 2 kWh/m^3. This reduction in energy consumption is exactly what makes CNTs a more economically sustainable option when it comes to the energy intensive process of desalination.

Environmental:

- Defined as a behavior that has a sustainable yield and and a sustainable waste disposal process
- Manufacturing of CNTs involves in chemical vapor deposition of ethylene. Results in harmful byproducts that compromise structural integrity of CNTs
- Nanotube synthesis process developed by Dr. Desire'e Plata at Duke University presents a 15-fold improvement in yield, 50% reduction in cost, and a decrease in hazardous product formation.
- Salt can be disposed in evaporation ponds, confined aquifers, or saline rivers that flow into estuaries