The Challenge of Water: A Tutorial on Thermodynamics

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waterCAMPwS

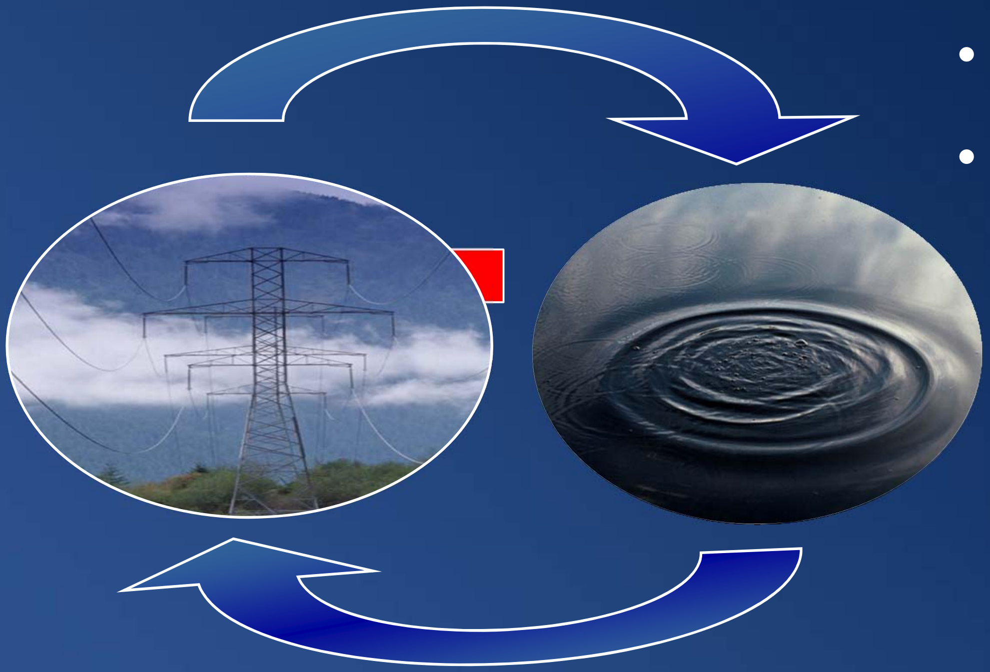
Water and Energy are Interdependent

Energy and power production require water:

- Thermoelectric cooling
- Hydropower
- Fuel Production (fossil fuels, H_2, biofuels)
- Emission control
- CO_2 separation and sequestration

Water production, processing, distribution, & end-use require energy

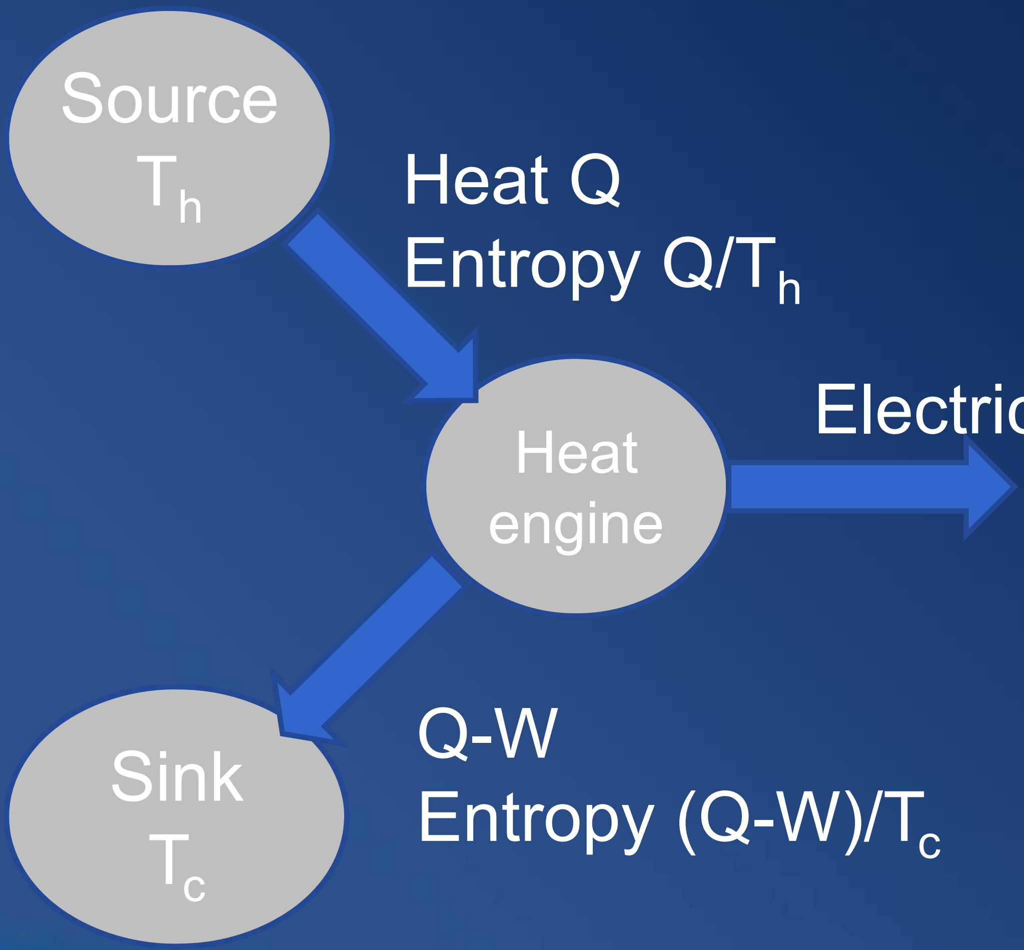
- Pumping
- Conveyance
- Treatment



Dr. Michael Hightower, Sandia National Labs, 2010

Second Law of Thermodynamics

$$\frac{Q-W}{T_c} \geq \frac{W}{T_h}$$



Source T_h

Heat Q
Entropy Q/T_h

Heat engine

Electrical energy W

Sink T_c

Q-W
Entropy $(Q-W)/T_c$

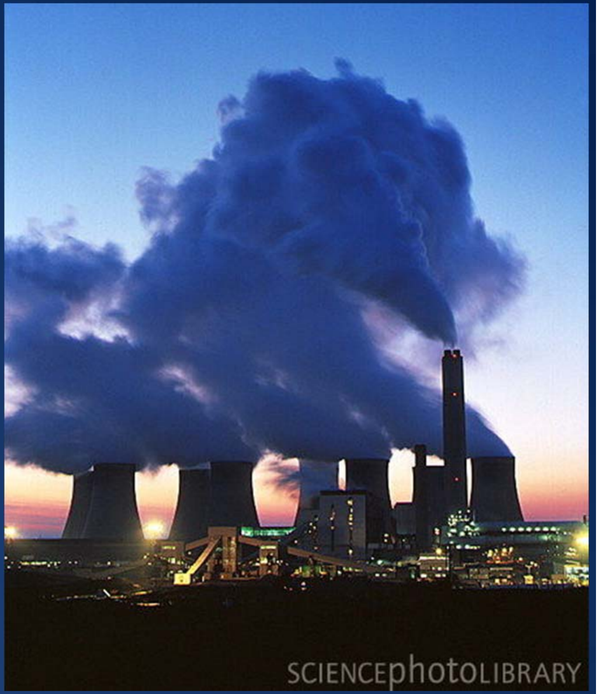
Second Law of Thermodynamics

$$\frac{Q-W}{T_c} \geq \frac{Q}{T_h} \qquad\qquad W \leq \left(1-\frac{T_c}{T_h}\right)Q$$

- In typical steam cycles (coal, nuclear) heat flow into cold heat sink is approximately the same as electrical power (Q-W) ≈ W (and comparable to heat lost to exhaust)
- Need to dissipate W of heat at as low of a temperature as possible.

Cooling requirements in power generation

- Most effective way to do this is with water, either by a heating a large volume by a small amount and then discharge to environment, or by evaporation.
- Discharge is warm and increases evaporation so overall consumption of water is similar in both cases.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Cooling requirements in power generation

- Heat of vaporization of water is 2 J/mm^3 or 2 GJ/m^3
- In other words, need to evaporate 0.5 m^3 of water per second for a 1 GW nuclear power plant.
- Order of magnitude the same as the household water use (in the US) of a small city of 100,000 (e.g., Champaign-Urbana, IL)

Why not use more air cooling?

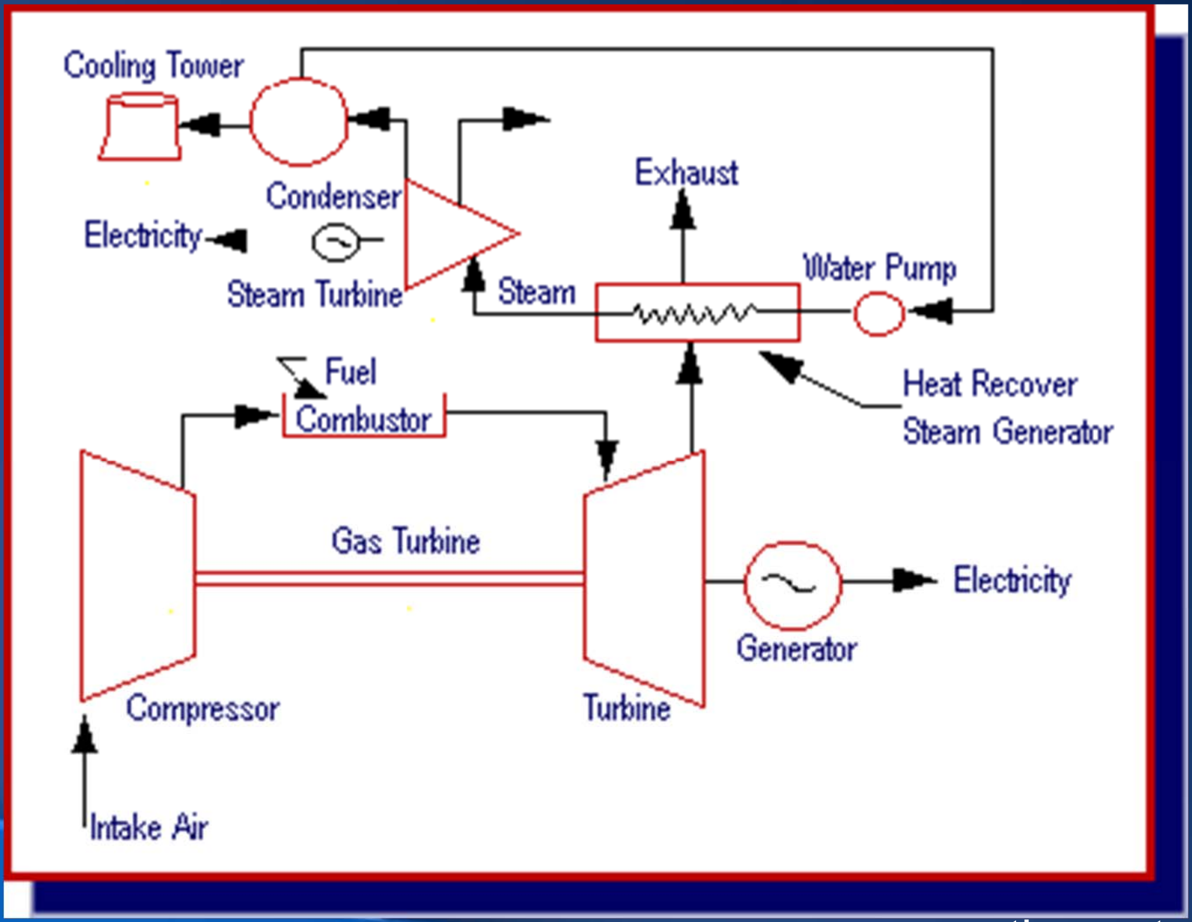
- Volume of air involved is huge.
  - Heat capacity per molecule is (7/2)k_B
  - Heat capacity per unit volume is (7/2)(P/T)≈1kJ/m^3-K at ambient conditions
  - With ΔT=10 K, requires nearly 10^5 more volume of air than evaporating water.
  - Enormous heat exchangers, fans, high capital costs.

Why not use more air cooling?

- Efficiency suffers: 0.1% per degree C.
  - Air temperature is not always as cold as available water. Worse in hot/climates where more air-conditioning is needed.
  - Additional thermal resistance because heat transfer is not as effective: basic property of effusivity (square root of the product of thermal conductivity and heat capacity per unit volume) is smaller by a factor of 100.
- Trade-off: do you want to reduce use of H_2O or CO_2 emission?

Why not use more air cooling?

- Combined cycle (natural gas powered) saves water and reduces CO_2 relative to coal.



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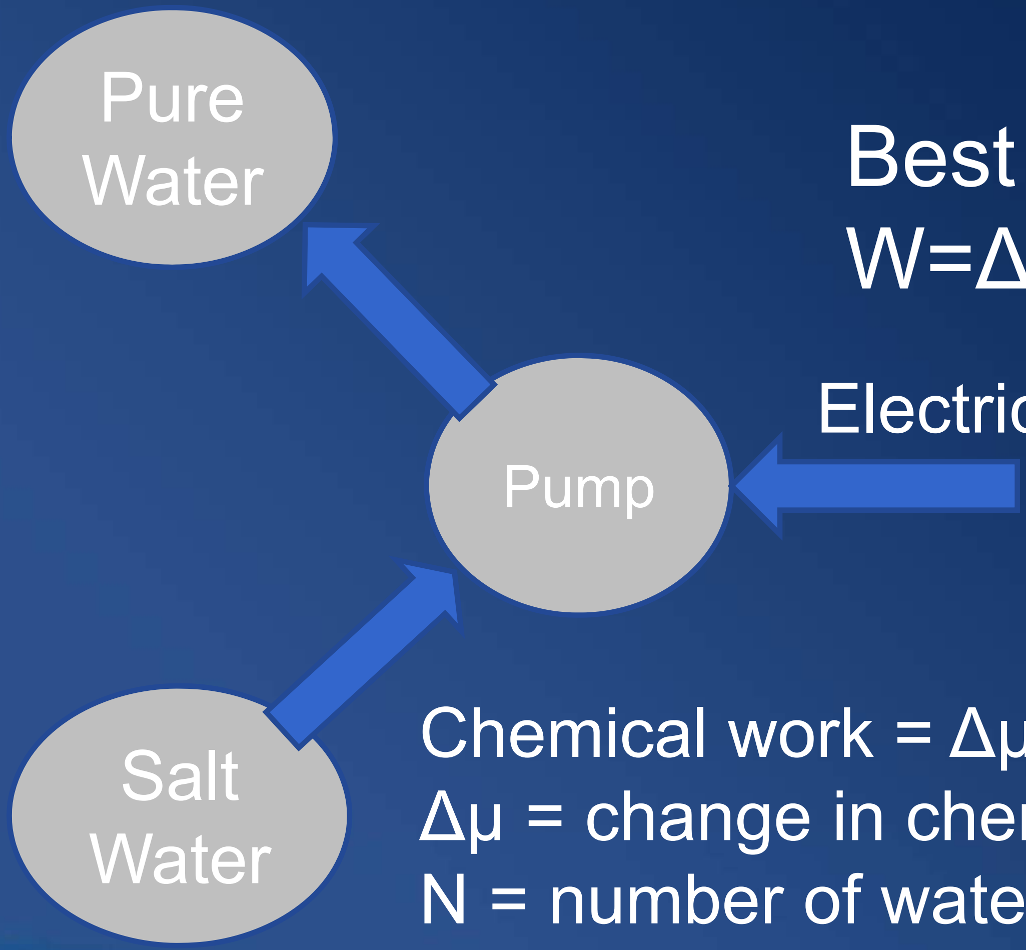
Thermodynamics of water purification

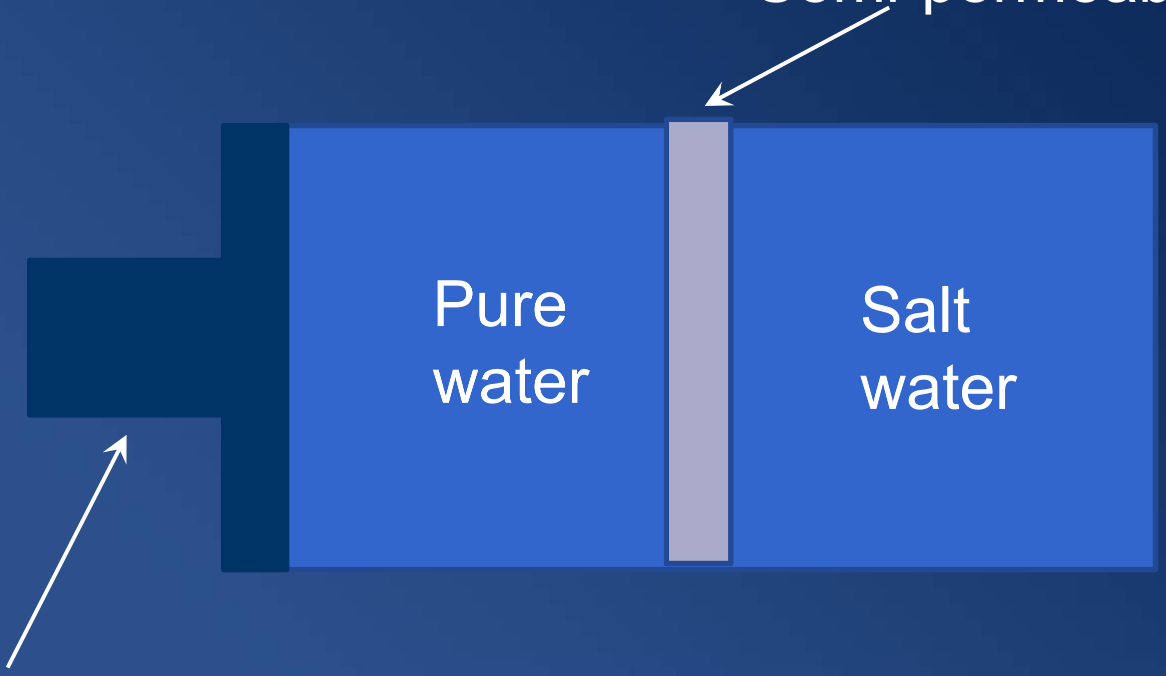


Best we can do is
$W = \Delta\mu N$

Chemical work = $\Delta\mu N$,
$\Delta\mu$ = change in chemical potential
N = number of water molecules

Thermodynamics of water purification

- Lowest possible energy is for a reversible process.



Semi-permeable membrane

Pure water

Salt water

Piston applies pressure = osmotic pressure Π

Thermodynamics of water purification

- For ideal solution of *n* ions per unit volume

$$\Pi = nk_BT$$

$$dV$$

- Differential work done in moving volume

$$dW = \Pi(dV)$$

- Integrate from initial to final osmotic pressure (assume 50% recovery)

$$W = k_BT \int_{V_0}^{(1/2)V_0} n\left(\frac{V_0}{V}\right) dV$$

Thermodynamics of water purification

- For 50% recovery, ideal solution, 3.5% by mass NaCl (V_0 = 2 m^3 to recover 1 m^3 pure water)

$$W = nV_0 k_B T \ln(2)$$

$$W = 3.8 \text{ MJ} \approx 1 \text{ kWh}$$

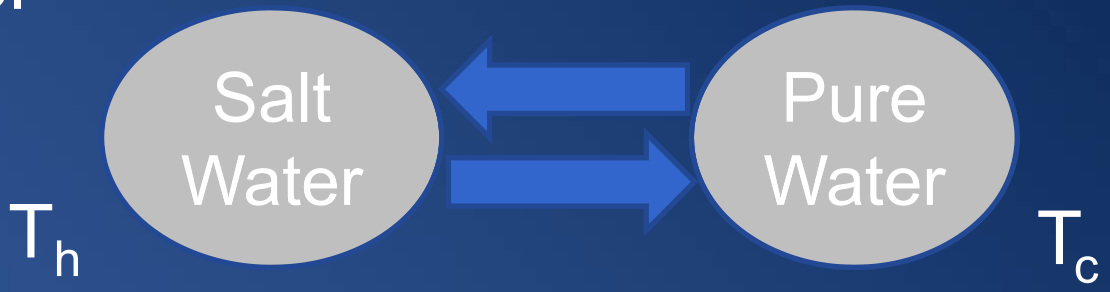
- No process can do better than this at 50% recovery. (For 0% recovery, no ln(2) term.)
- State-of-the-art RO is only a factor of 2 higher than this limit.

Is 1 kWh = 3.6 MJ a lot of energy?

- Electrical power cost is about $0.10
- Heat 10 L of water to boiling point
- Light a CF light bulb for a few days
- Run a refrigerator for ½ day
- Do 3600 google searches
  - One google search consumes as much energy as state-of-the-art RO uses to purify a small cup of water.

Thermodynamic limits for a distillation process are the same

- For a reversible process, we have to make the vapor pressures equal (almost) but that means the temperature of the salt water is higher



Approximate heat input: $$dQ = \Delta H \left(1 - \frac{T_c}{T_h}\right) dV$$

ΔH=enthalpy of vaporization per unit volume

Thermodynamic limits for distillation

- Real-world distillation processes (multi-stage) work far from the thermodynamic limit.

$$dW = \Delta H \left(1 - \frac{T_c}{T_h} \right) dV$$

- Even for ΔT=10 K, this is 15 times worse than the thermodynamic limit.

But maybe sometimes heat is free, i.e., “waste heat”?

- Low-grade (low temperature) heat source that is not feasible to use in electrical power generation might be used to purify water.

- But keep in mind that high efficiency power generation uses low temperature heat sinks. Not much of the heat is “wasted”