Heat Storage for Solar Thermal Power Plants

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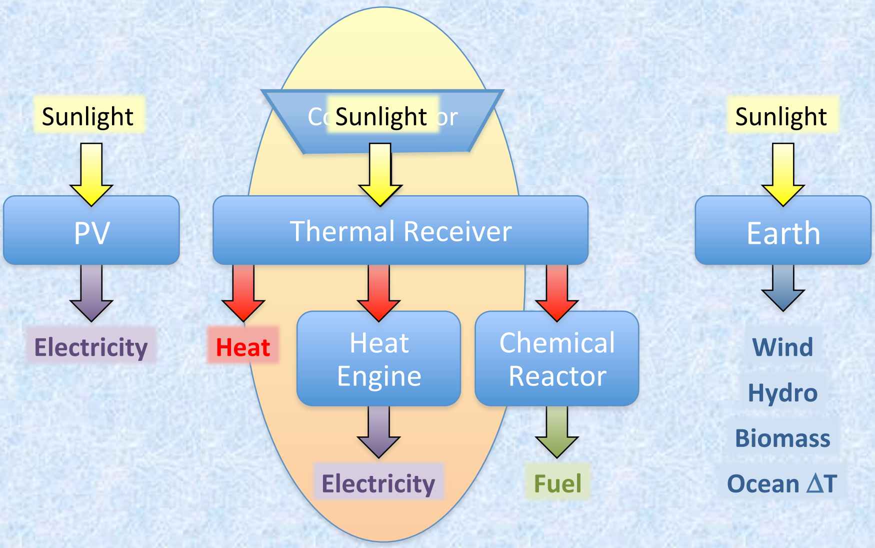
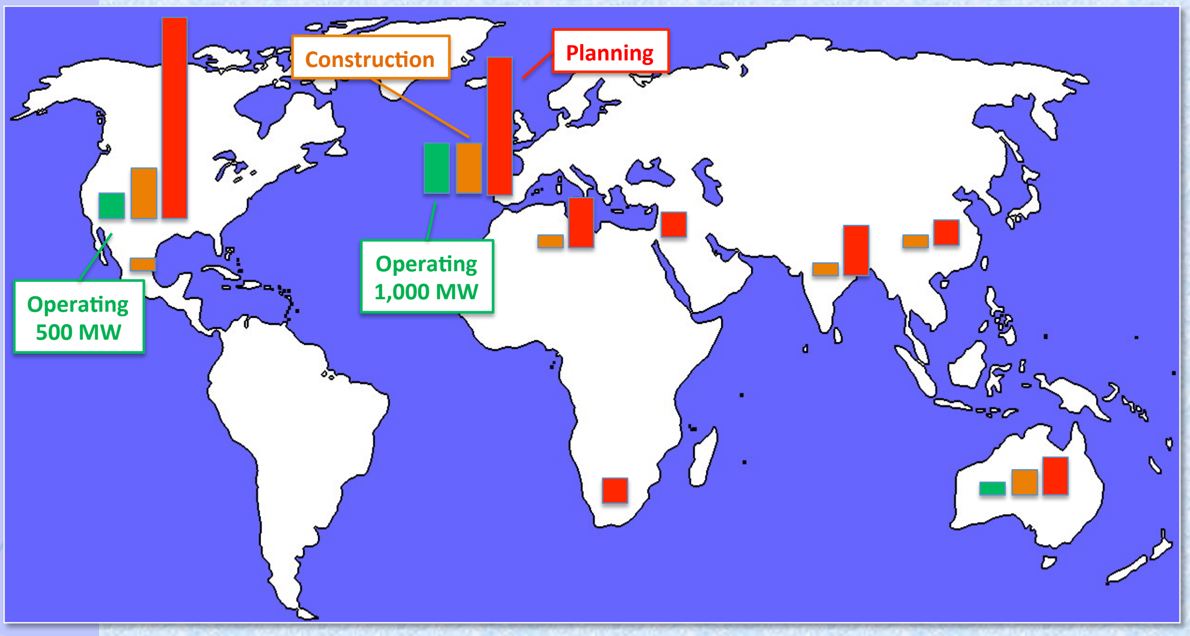
Solar Energy Conversion



Solar Thermal Power Plants



Storage

Challenge:

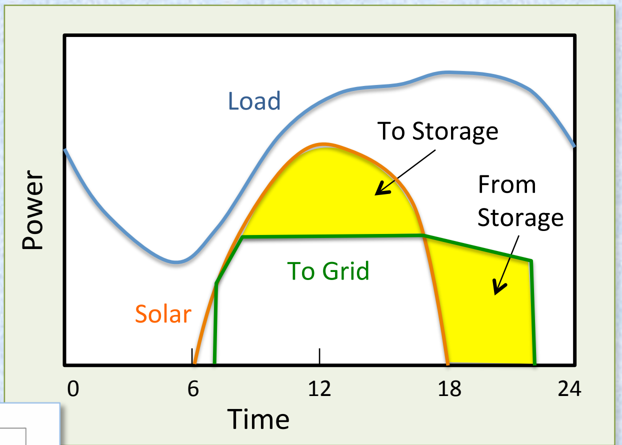
Mismatch supply & demand

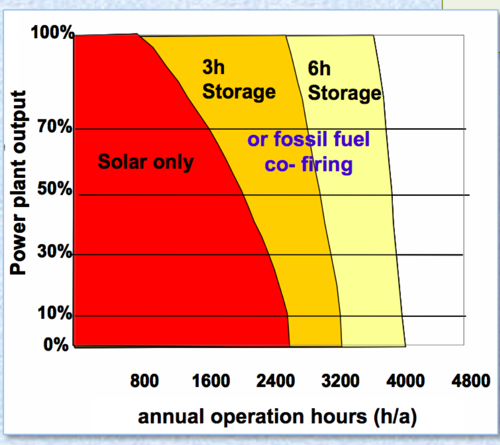
Goals:

Higher solar contribution

Dispatchable power

Reduce part-load operation





Storage types

Electrochemical (batteries)

Mechanical (pumped hydro, flywheel)

Electromagnetic (capacitor, SC coil)

Electricity → Storage → Electricity

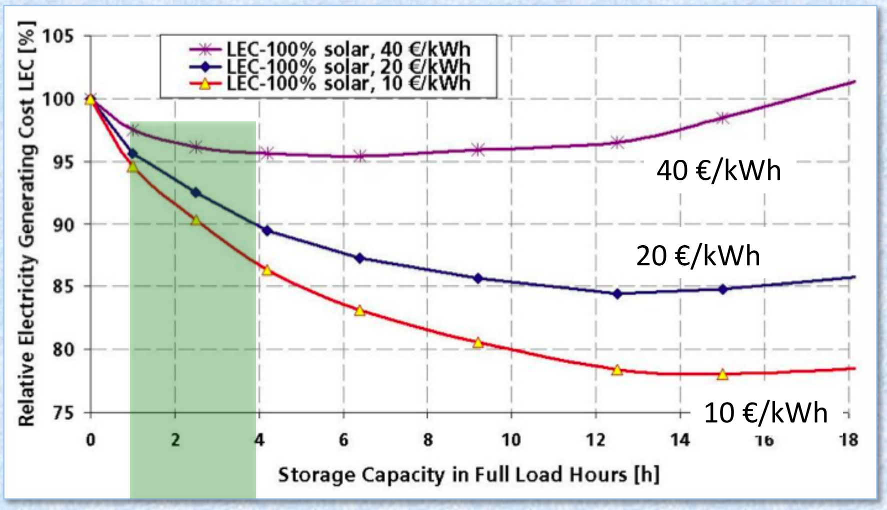
Thermal storage

Store heat prior to conversion

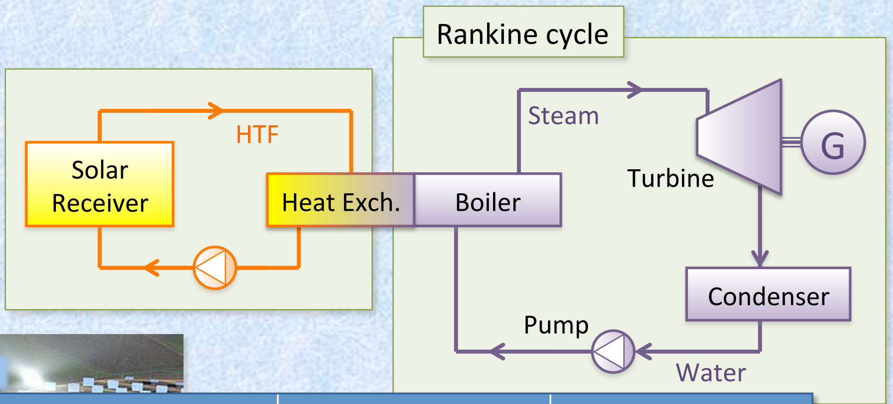
Storage Impact on Cost

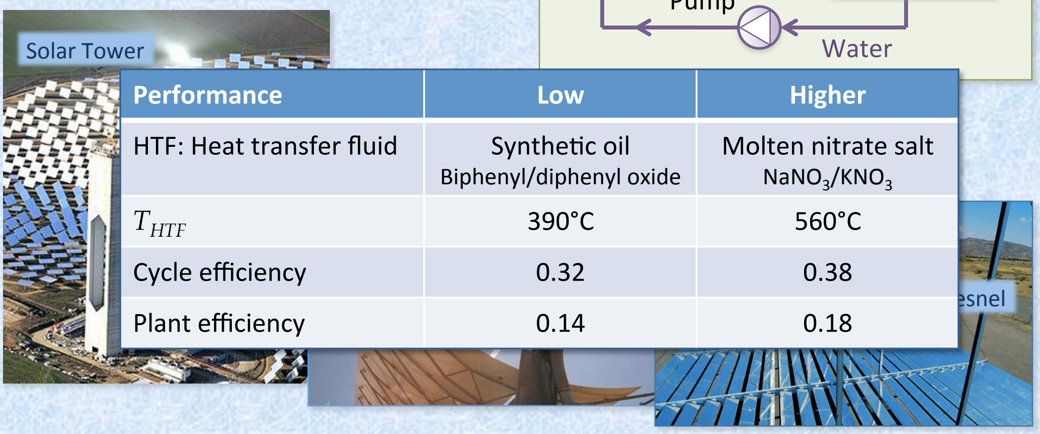
+ Higher investment cost

– More operation hours → better use of installed equipment



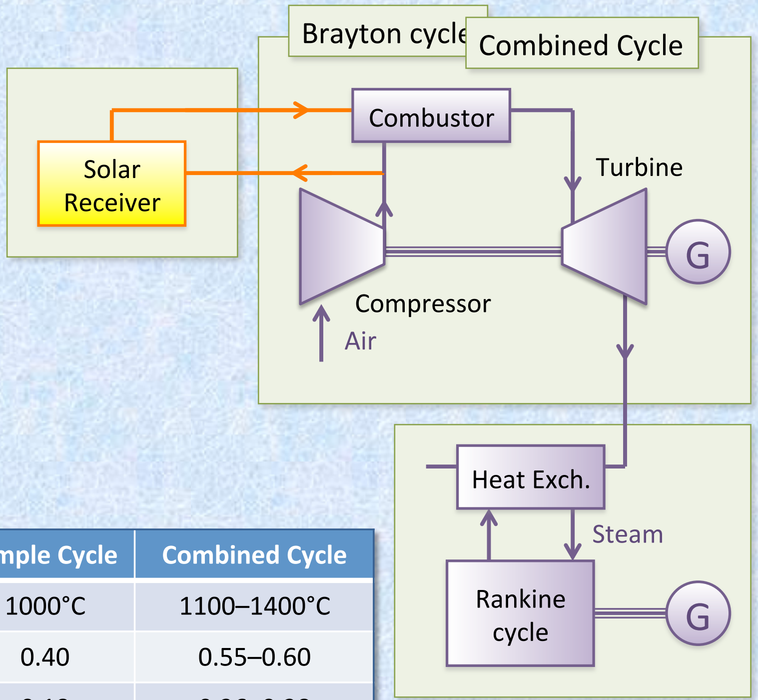
Thermal Conversion (Steam)





Performance	Low	Higher
HTF: Heat transfer fluid	Synthetic oil Biphenyl/diphenyl oxide	Molten nitrate salt $NaNO_3/KNO_3$
T_{HTF}	390°C	560°C
Cycle efficiency	0.32	0.38
Plant efficiency	0.14	0.18

Thermal Conversion (Air)



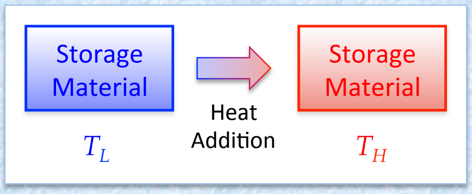
	Simple Cycle	Combined Cycle
T_{MAX}	1000°C	1100–1400°C
Cycle efficiency	0.40	0.55–0.60
Plant efficiency	0.18	0.26–0.28

Heat Storage Principles

Sensible heat

Stored energy:

$$\Delta E = mC(T_H - T_L)$$

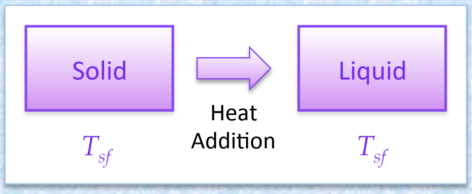


Latent heat

Phase Change materials (PCM)

Stored energy:

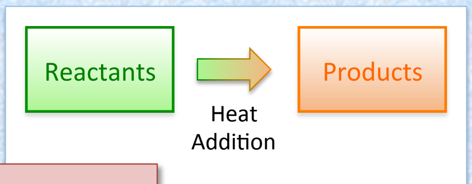
$$\Delta E = m \cdot e_{sf}$$



Thermochemical storage

Stored energy:

$$\Delta E = m \cdot \Delta h$$



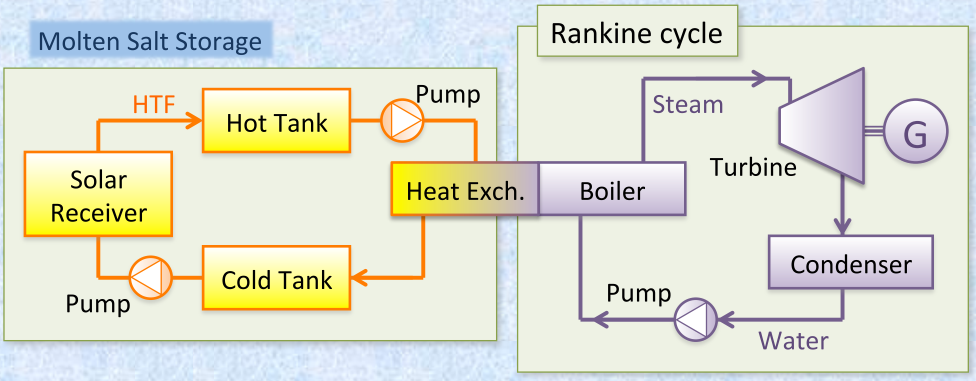
Why many options?
Is there a 'best' option?

Sensible Heat Storage

Storage materials

Solid
- Concrete
- Ceramics
- Rocks, pebble bed

Liquid
- Water? < 100°C
- **Molten nitrate salt <565°C**



Molten Salt Storage

Direct storage: HTF = Storage material
Indirect:
HTF → Storage material → Steam

"**Solar Salt**": 60% $NaNO_3$ + 40% KNO_3

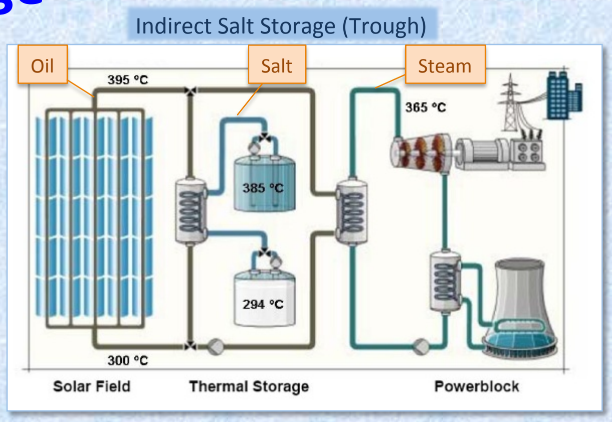
Heat storage capacity
Tower 285–565°: 425 kJ/kg
Trough 285–385°C: 150 kJ/kg

Example: 100 MW_e, 4 hours

	Tower	Trough
Tons of salt	8,500	24,000
Tank size (D×H)	24×12	33×17

Advantages
Heat loss <1%
Stable operation from storage

Disadvantage
Freezing in pipes (@ T=240°C)

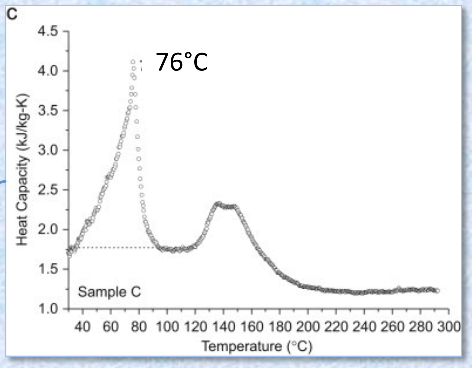


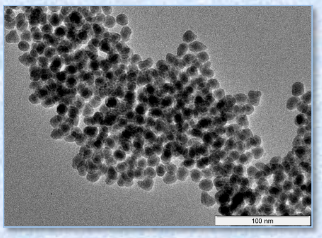
Molten Salt: Materials

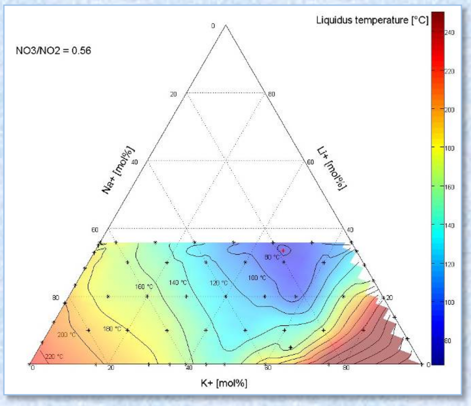
Lower melting temperature < 150°C

Higher operation temperature > 600°C

- Liquid metals?
- Eutectics: e.g., $Ca(NO_3)_2/KNO_3/NaNO_3$
  - $NaNO_3/NaNO_2/KNO_3$ (142°C)
  - $LiNO_3/NaNO_3/KNO_3$ (118°C)
- Composites
  - $KNO_3/NaNO_3 + SiO_2$ nanoparticles (120°C)



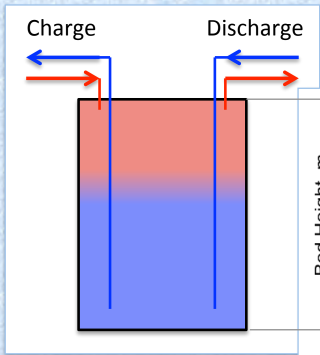




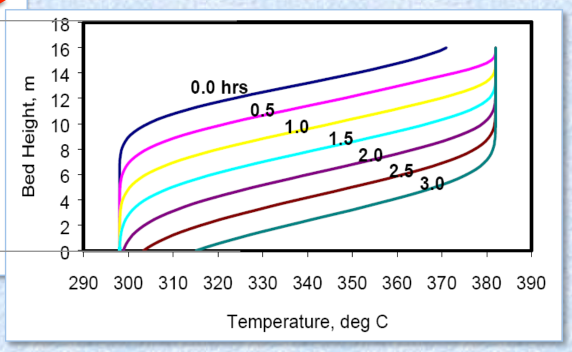
Additional requirements:

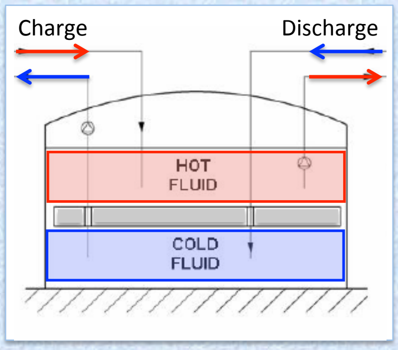
- Stability @ high T
- High specific heat
- Low vapour pressure
- Compatibility with piping etc.

Molten Salt: Configuration



Thermocline tank





Floating barrier

- Single tank
- Thermal separation

Advantages

- Single tank
- Add inexpensive filler

Disadvantages

- Thermocline degradation

Solid Storage

Concrete + pipes

HTF: steam

Use: Superheat + Preheat

Heat storage capacity

60–560°: 500 kJ/kg

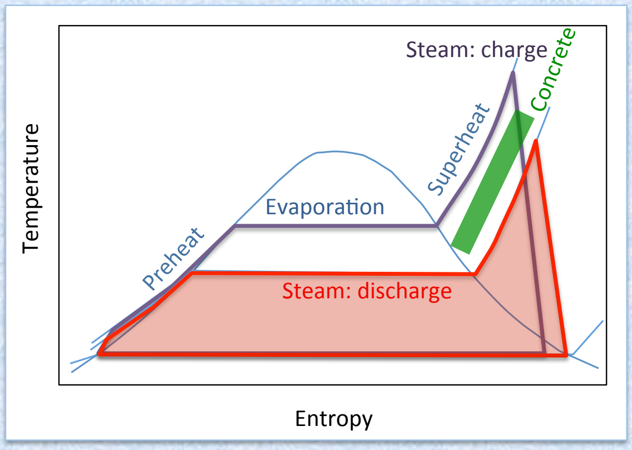
Advantages

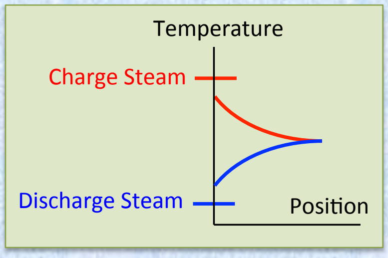
Inexpensive

No danger of freezing

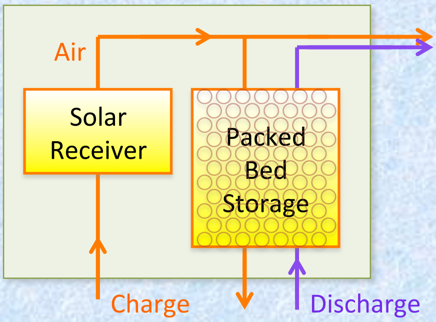
Disadvantages

Conductivity < 2 Wm^{-1}K^{-1}





Solid Storage

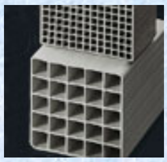


Packed Bed storage

HTF: air

Storage medium: rock / ceramic

Single tank thermocline



Heat storage capacity

Material	ΔT=300 K	500 K
Rock	240 kJ/kg	400 kJ/kg
Magnesia	340 kJ/kg	560 kJ/kg

Advantages

Single tank

Inexpensive HTF (air)

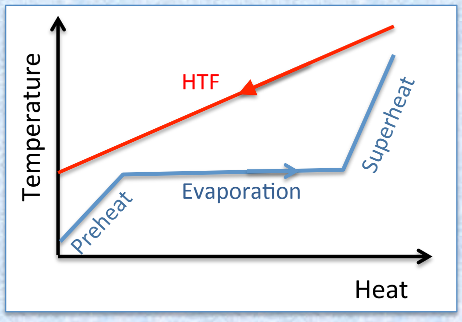
Inexpensive storage medium (rock)

Disadvantages

Thermocline degradation: conduction + dispersion

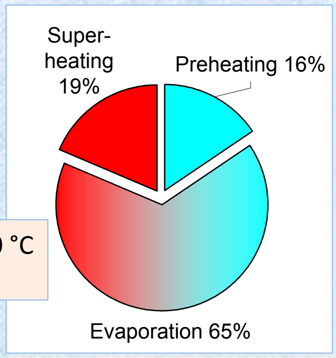
Air pumping power

Storage for Steam Evaporation

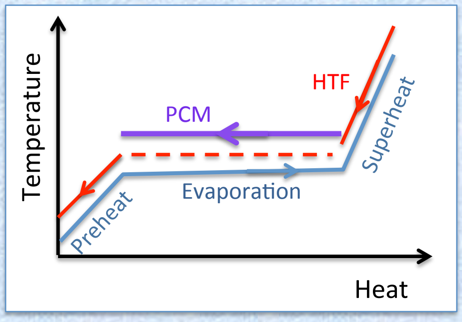


Sensible Heat:

Large ΔT → entropy generation
"Pinch point" in heat exchanger



260 °C / 400 °C
107 bar



Latent Heat

Phase Change Material (PCM)

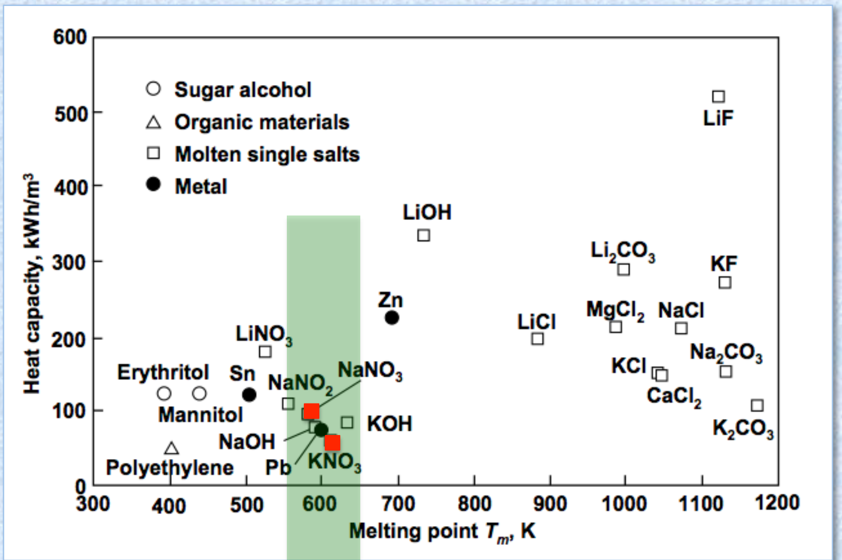
Constant T, match evaporation
Small ΔT
Separate sensible heat storage
for preheat, superheat

PCM

Material selection citeria:

Melting temperature
Latent heat
Corrosion
Cost

$NaNO_3$
306°C
180 kJ/kg



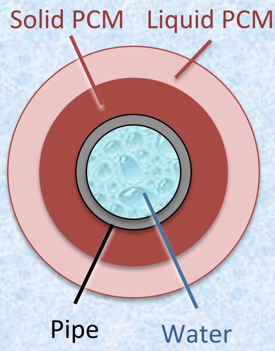
Steam pressure:
100–150 bar

Heat Transfer in PCM

Main challenge: **low thermal conductivity**

$k < 1\,\mathrm{W m^{-1} K^{-1}}$

High & variable thermal resistance

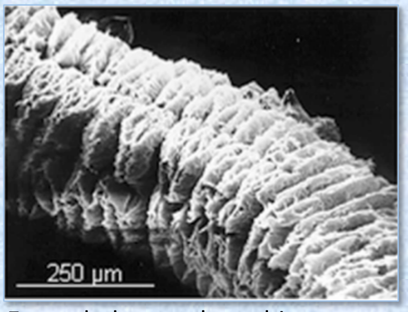


Heat transfer solutions

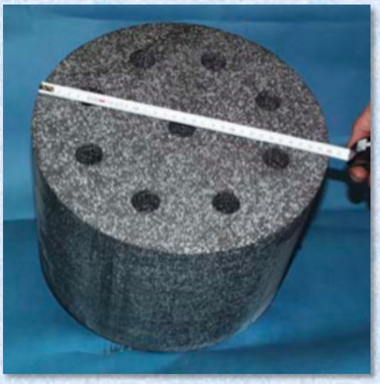
- Composite PCM
- Extended surfaces (fins)

Composite:

Salt PCM + graphite particles $k < 10\,\mathrm{W m^{-1} K^{-1}}$

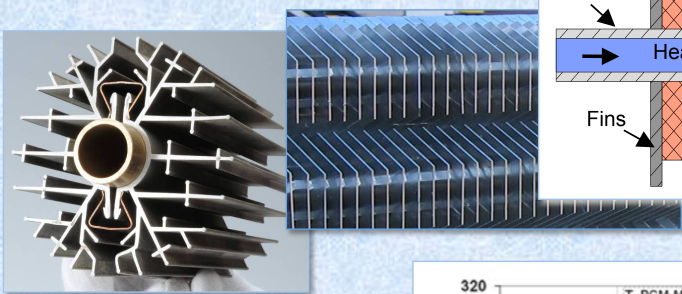


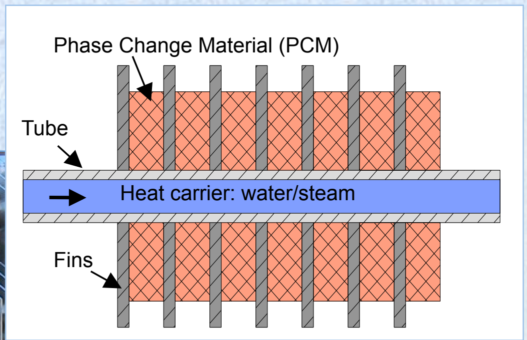
Expanded natural graphite

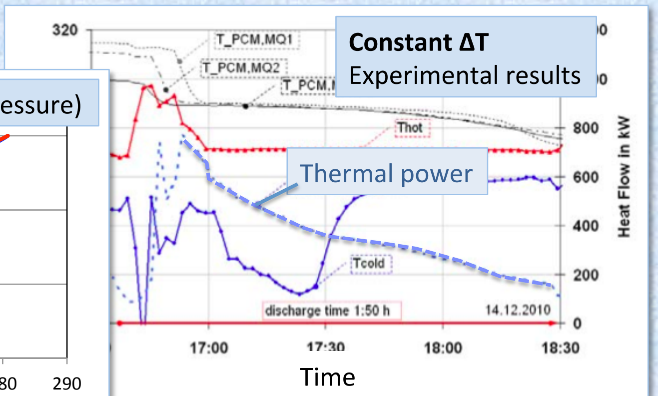


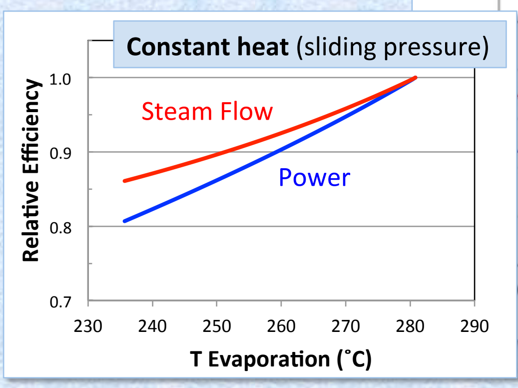
Extended surface

Fins: graphite, aluminum







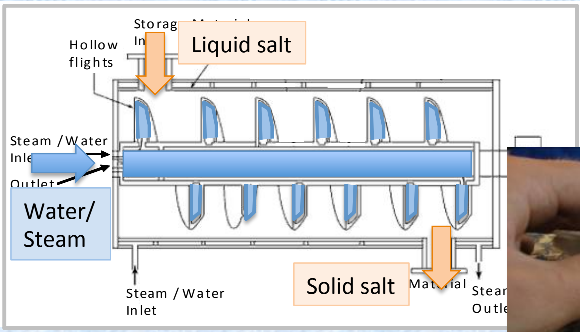


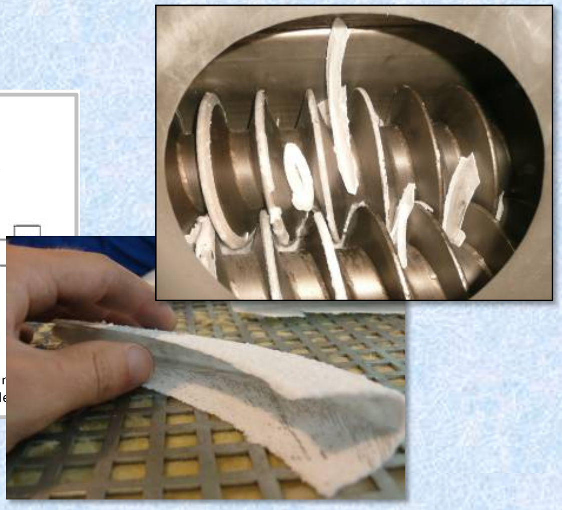
Advanced PCM Approaches

Screw Heat Exchanger

Liquid, solid stored separately

Mechanical separation of solid



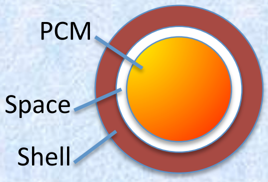


Encapsulated PCM

Porous bed with small PCM capsules

Shell: ceramic, metal?

Graded T_{melt} in tank



Thermo-Chemical Storage

- High storage density
- Wide temperature range
- Loss-free long-term storage
- Heat transport possible

$$CH_4 + H_2O + \Delta H \rightarrow 3H_2 + CO$$
$$CH_4 + CO_2 + \Delta H \rightarrow 2H_2 + 2CO \qquad \Delta H \approx 12{,}000\ \mathrm{kJ/kg}$$

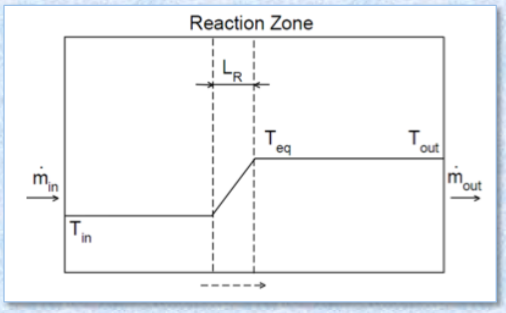
Well known process, > 800°C
Expensive catalyst
Gas: large volume for storage

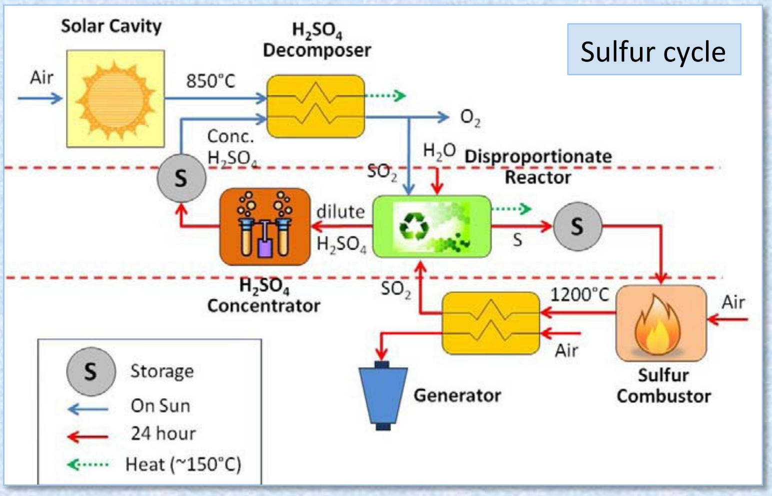
$$Ca(OH)_2 + \Delta H \rightleftharpoons CaO + H_2O \qquad \Delta H = 1{,}340\ \mathrm{kJ/kg}$$

Well known process, 300–700°C
Low cost material
Completely reversible
No complicated side reactions

$$M_xO_{y+z} + \Delta H \rightleftarrows M_xO_y + \frac{z}{2}O_2$$

Candidates: Zn, Fe, Mn, Co…
Temperatures: usually > 1,000°C
Full or partial oxidation
Solid: powder, packed bed





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Conclusions

Energy storage is key issue → dispatchability & efficiency

Current storage solutions: limited applicability

Advanced storage materials

Temperature range, heat capacity, thermal conductivity, stability, corrosion, cost

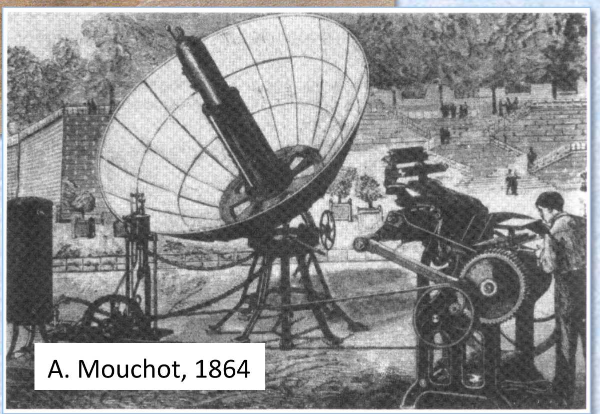
Heat transfer solutions

High conductivity, high surface area

Solar thermo-chemistry: storage of the future (?)

Solar Thermal Conversion

Archimedes, ca. 215 BC



A. Mouchot, 1864