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SFERA-III 2nd Summer School
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Almería (Spain)

Lecture:
Thermal storage for SHIP applications

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Content:

- Designing Thermal Storage Systems
- TES for Steam as HTF
- TES for Water as HTF
- TES for Air as HTF
- Final comments

Designing Thermal Storage Systems -1

Energy Source

Solar Thermal

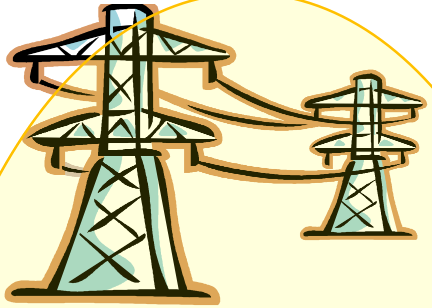
Waste heat

Other renewables

Thermal Storage

Thermal Energy
(steam, gas,T,P)

Applications



Power generation

Industrial Processes

Domestic heating&cooling

Designing Thermal Storage Systems -2

Solar Thermal

- ✓ DGS technology

Waste heat

Thermal Storage

Thermal Energy
(steam, gas,T,P)

Industrial Processes

- ✓ Steam as HTF
- ✓ Water as HTF
- ✓ Air as HTF
- ✓ Softer requirements

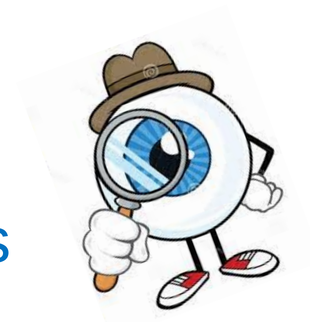
Designing Thermal Storage Systems -3

- ✓ **Plant integration** ← energy source & sink
- ✓ **Material** ← Storing energy mechanism
  - if $\Delta T = 0$ → Latent or Thermochemical Storage
  - if $\Delta T \neq 0$ → Sensible Storage

Storage capacity ≡ Stored energy

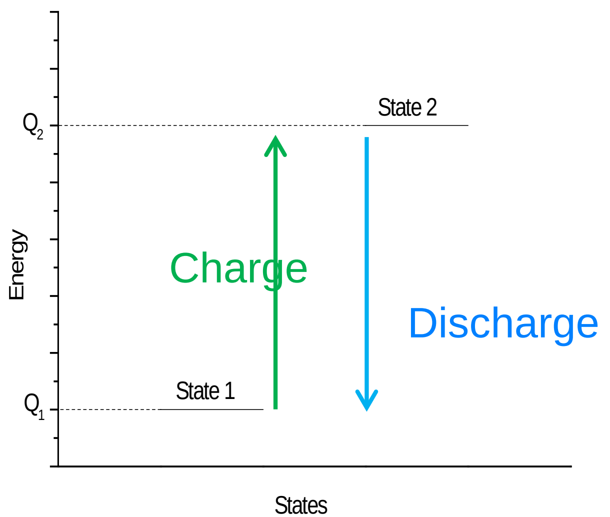
- ✓ **Efficient heat transfer** to/**from** the TES
  - Conducction
  - Convection
  - Radiation

Discharge process



TES for DSG and/or steam as HTF : LATENT STORAGE

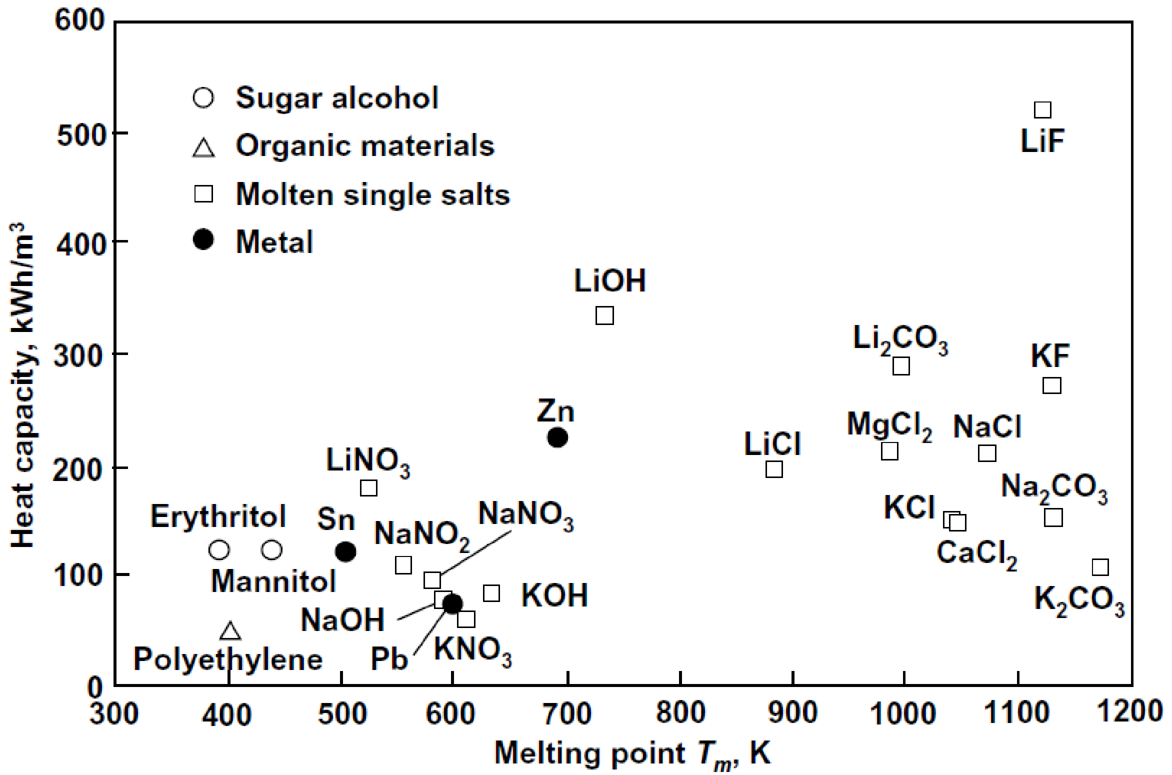
- The storage medium **undergoes a phase change** ⇨Phase change material (PCM)



- Charge process: $Q_{TES}=Q_2-Q_1=m_{PCM}\ \Delta H_{phase} > 0$
- Discharge proc.: $Q_{TES}=Q_1-Q_2= m_{PCM}\ \Delta H_{phase} < 0$
- Storage capacity, Q_{TES}, depends on
  Latent enthalpy, ΔH_{phase}
- PCM is firstly define by its phase change temperature, T_{change_phase}

LATENT storage – PCMs examples

✓ Adequate phase change temperature: T_m (🡐Plant Integration)

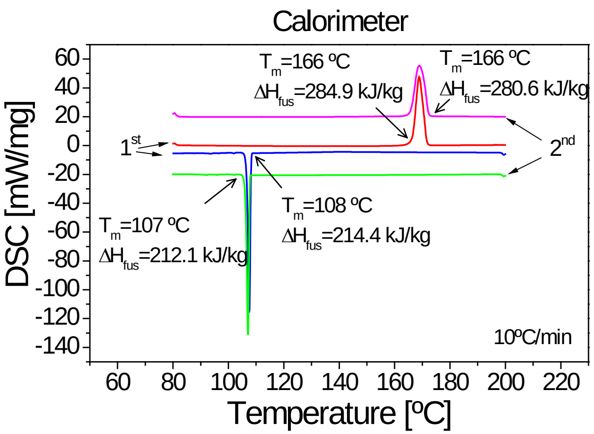


➢ As high phase change enthalpy as possible

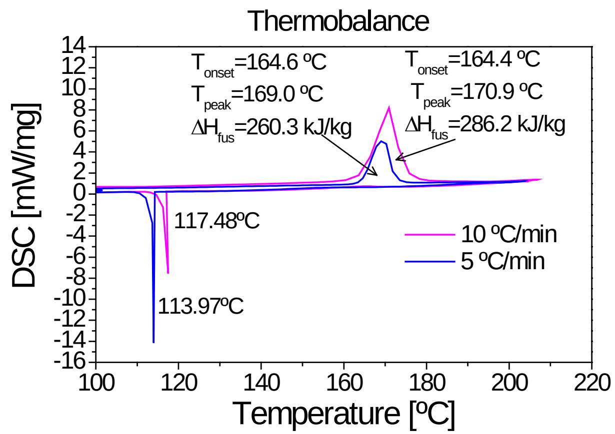
Akira Hoshi et al. Solar Energy 79 (2005) 332

LATENT storage – PCMs requirements

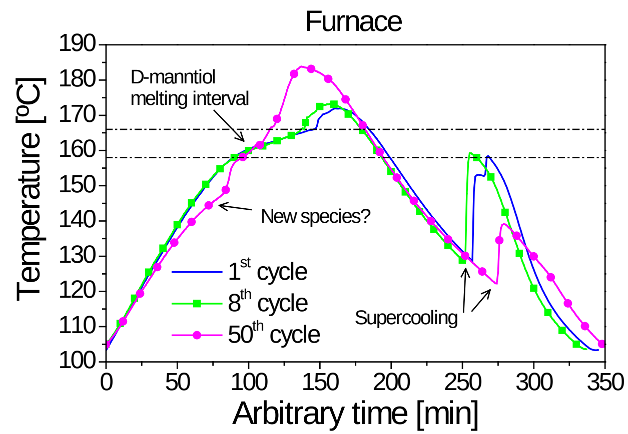
- ✓ Adequate phase change temperature: T_m
- ✓ Reversible process: low supercooling
  - Supercooling == difference between the onset temperatures of melting and freezing
  - Most materials exhibit some supercooling behavior (between 1 to 50ºC)
  - It uses to be magnified by DSC measurements



Heating peak: 166ºC
Cooling Peak: 107 ºC
60ºC supercooling!!!



Enthaly values seem to depend on heating/cooling rate



Furnace measurements more reliable (no information on ΔH_{phase})

[1] *Bayón& Rojas, Characterization of organic PCMs for medium temperature storage, EMR2015 Conference, Madrid (Spain), February 2015.*

LATENT storage – PCMs requirements

- ✓ No sublimation or vaporization in the working temperature range
- ✓ No degradation in the working temperature range
- ✓ Stability under cycling
  - **Careful with the PCM candidates proposed in the literature!!!**

Salicylic acid

Example of gas emissions close to melting temperature

Hydroquinone

Example of gas emissions close to melting temperature & degradation

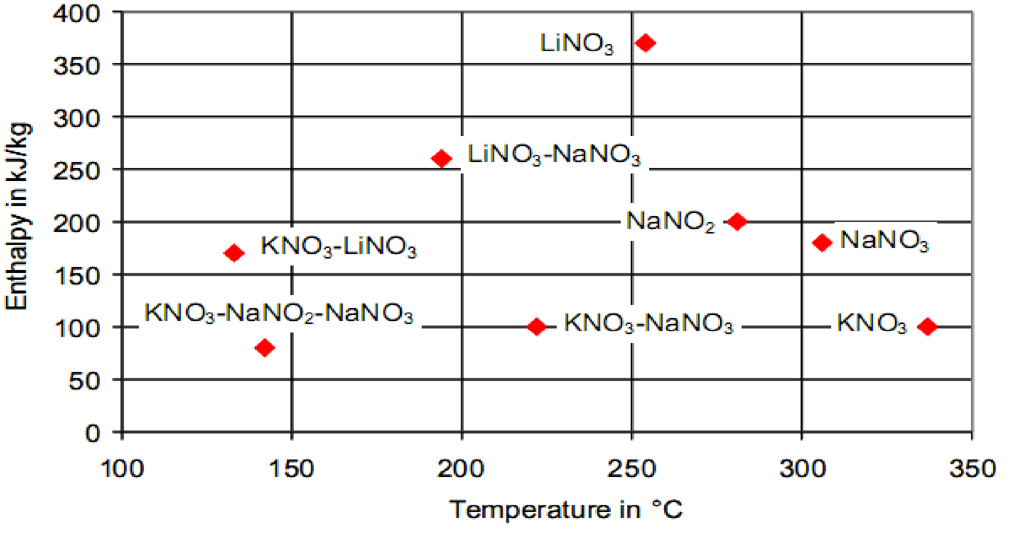
D-Mannitol

Example of degradation

LATENT storage – Efficient heat transfer

- Solid to liquid transitions → **high effective thermal difussivity** required

- INORGANIC salts

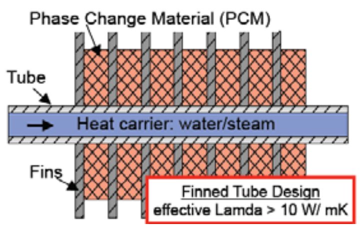


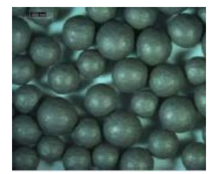
Thermal conductivity <1W/mK
High thermal resistance!!!

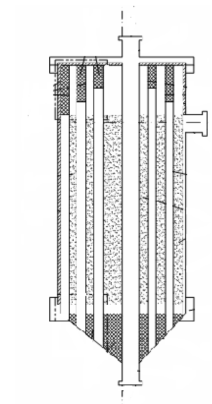
Heat transfer enhacement design required

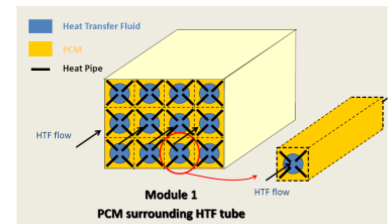
LATENT storage – Efficient heat transfer

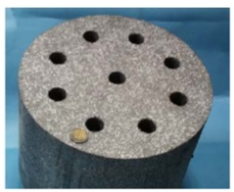
- Different and multiple approaches worldwide











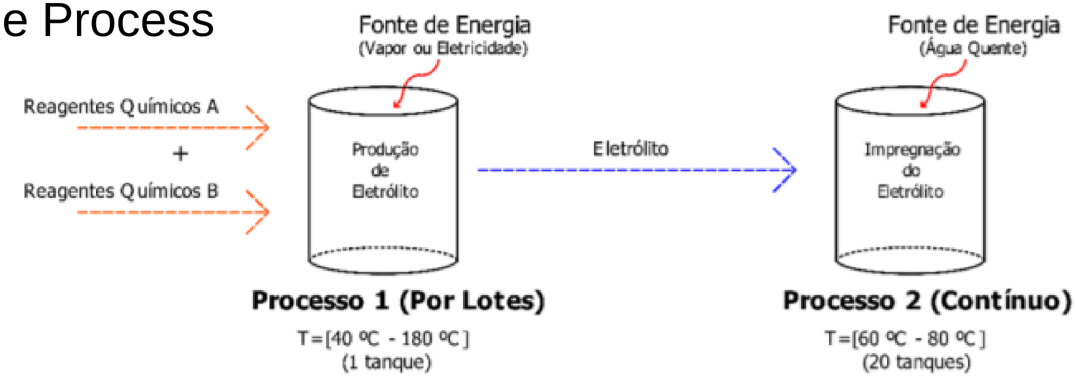
……………etc.

Heat transfer enhancers' cost has to be taken into account

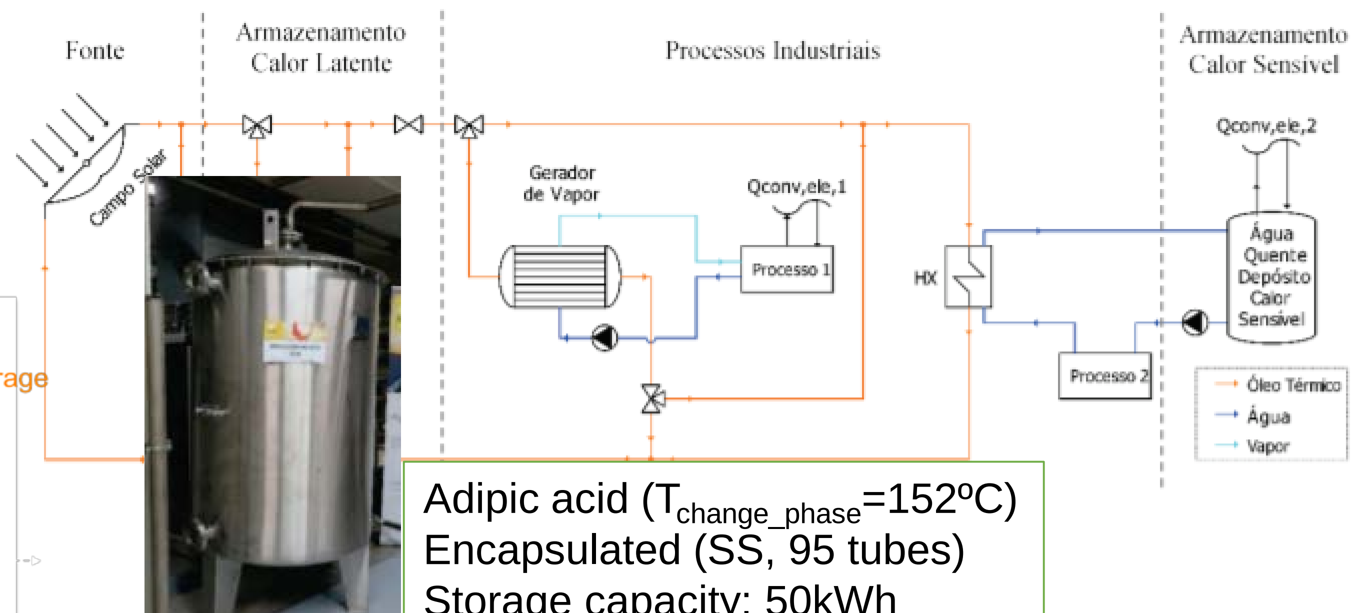
LATENT storage – SHIP in KEMET Elect. Portugal

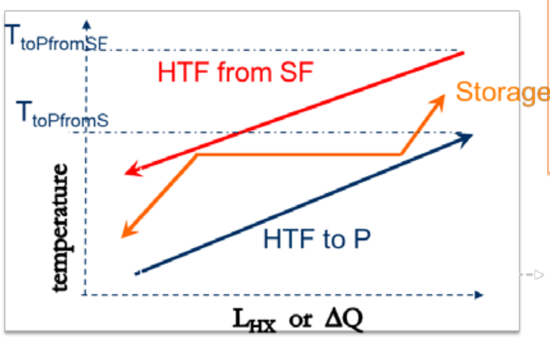
(Évora, Portugal)

The Process



The System





Adipic acid (T_{change_phase}=152ºC)
Encapsulated (SS, 95 tubes)
Storage capacity: 50kWh

Eusébio et al. "PROYECTO SHIP", CIES2020

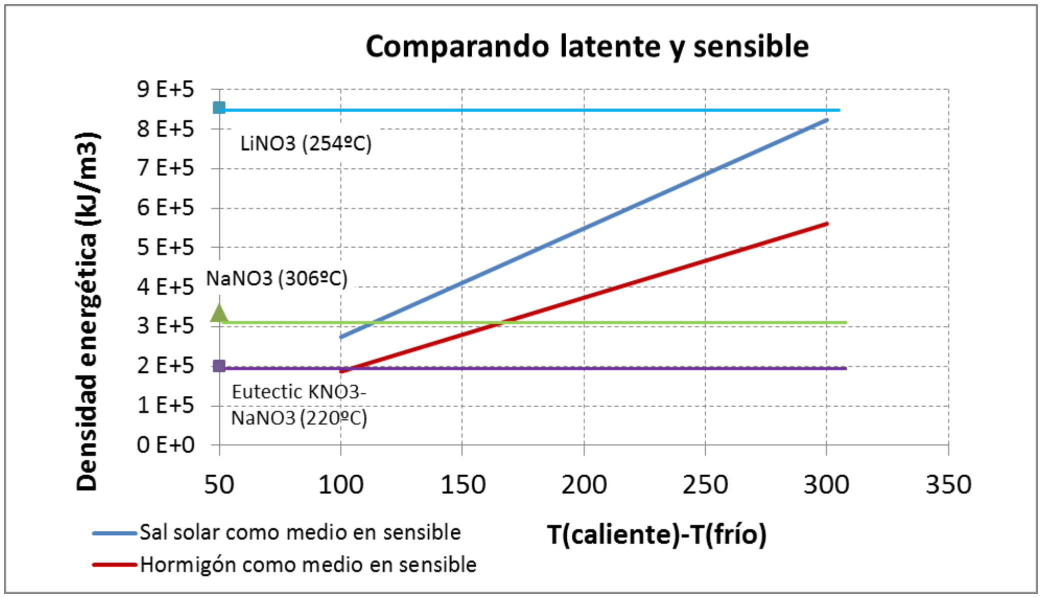
TES for WATER as HTF:

SENSIBLE STORAGE

There is a temperature change in the storage medium

Δ**Q=mC$_p$ (T$_2$-T$_1$)** ⇨(>0 in charge; <0 in discharge)

- **Storage capacity** (kWh) depends on temperature interval in the storage medium⇨T_2-T_1



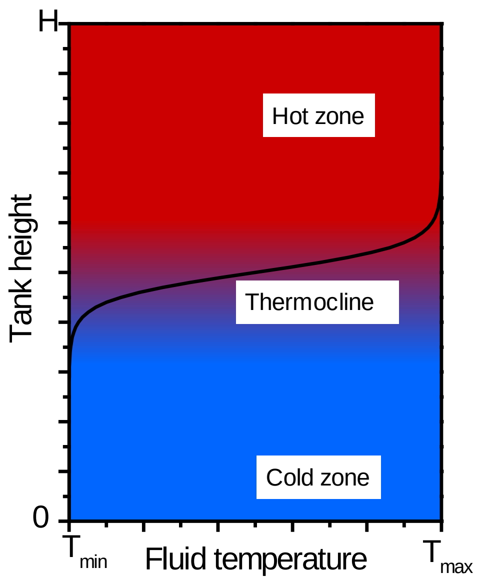
SENSIBLE storage – MEDIUM requirements

- ✓ **Stable** in the temperature range of operation, **(T_1, T_2)**
- ✓ **Low vapor pressure for liquid media** → avoiding presurized tanks
  - Water has to be under pressure: 30bar/230ºC; 100bar/311ºC (*)
- ✓ **Non explosive or hazardous materials**
- ➢ **Low price materials**
- ➢ **High volumetric thermal capacity, ρC_p**
  - Solar salt (60%NaNO3+40%KNO3): ~2800 kJ/m³ ºC
  - Sinthetic oil: ~ 1900 kJ/m³ ºC
  - water: ~ 4200 kJ/m³ ºC
  - concrete: ~2500 kJ/m³ ºC
  - rocks: ~2700 kJ/m³K
  - Vitrified industrial wastes (Cofalit y Plasmalit): ~3000 kJ/m³K
  - Magnesia : 3390 kJ/m3K

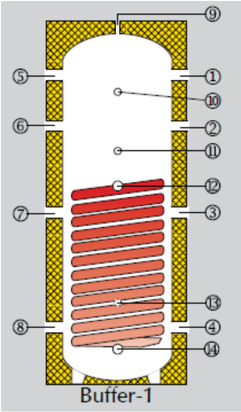
(*)water critical point: 374°C/218bar

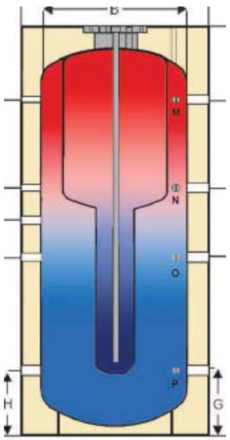
SENSIBLE storage – WATER TANKS

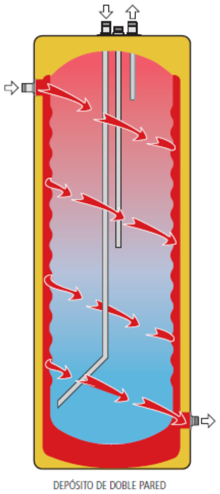
- Well-known technology (🡐 DHW apllications)
- **Thermocline tank**: the thinnest the thermal gradient, the best exergy



A lot of designs…..







Storage temperature below 100ºC

SENSIBLE storage – AIR as HTF

Designing Thermal Storage Systems -2

hermal
nergy
(steam,
gas,T,P)

Industrial Processes

- ✓ Steam as HTF
- ✓ Water as HTF
- ✓ Air as HTF
- ✓ Softer requirements

esalination"

Slide 4

SENSIBLE storage – MEDIUM requirements

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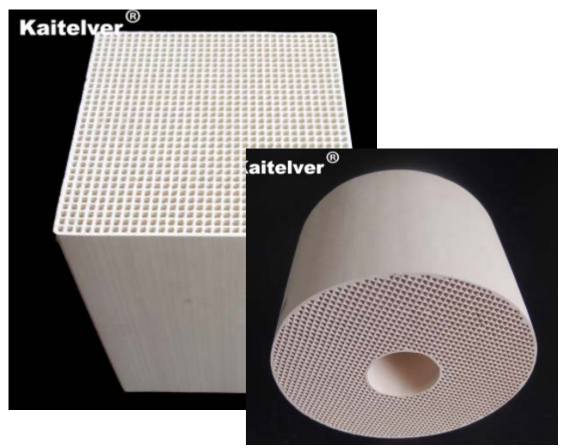
TES for AIR as HTF - REGENERATORS

- Also known as Regenerative HX
- Used since the Industrial Revolution

  Furnaces in glass making, heated by combustion exhaust gases **(T>1000ºC)**

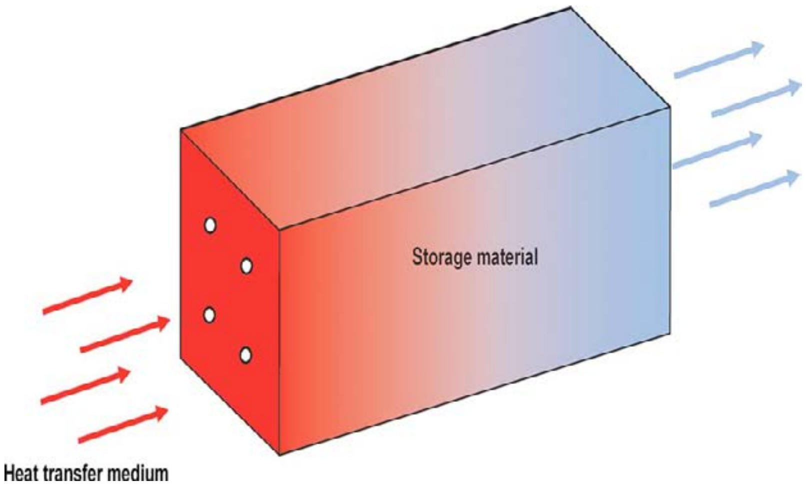
Magnesia Bricks
(k~5W/mK)

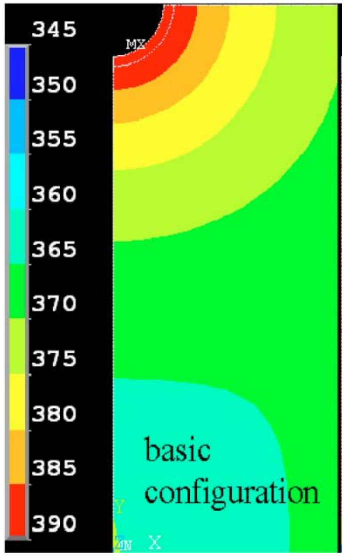


Sic & cordierite ceramic honeycomb
(k>3W/mK)

TES for AIR as HTF – other solids (CONCRETE) -1

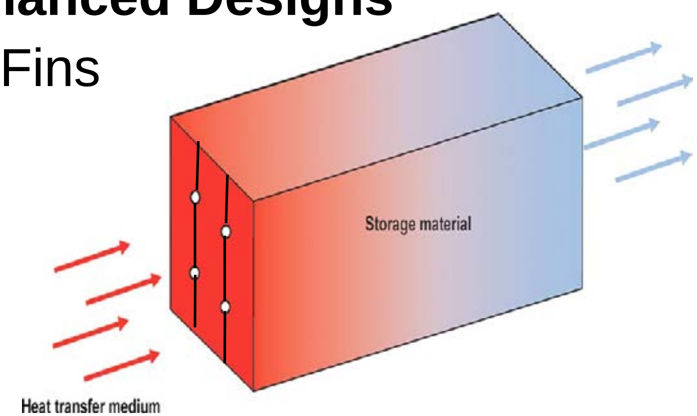
- **(Special) Concrete** (~2500 kJ/m³K), industrial wastes (Cofalit, Plasmalit)
- Mechanical strength is critical
- **Conduction** is the main heat transfer mechanism ($k_{típica} \leq 1.5$ W/mK)

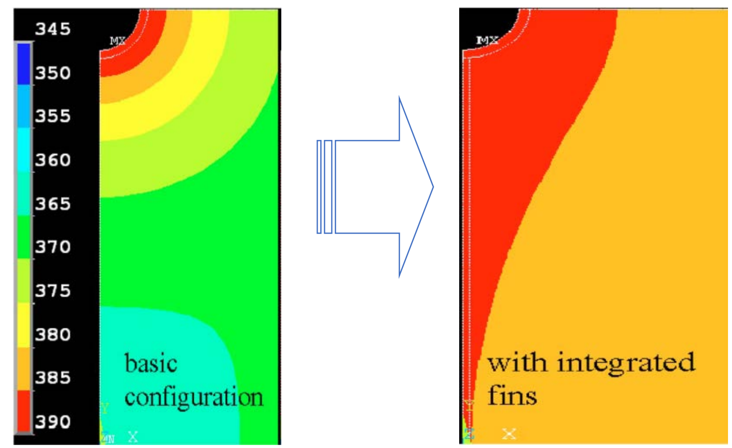




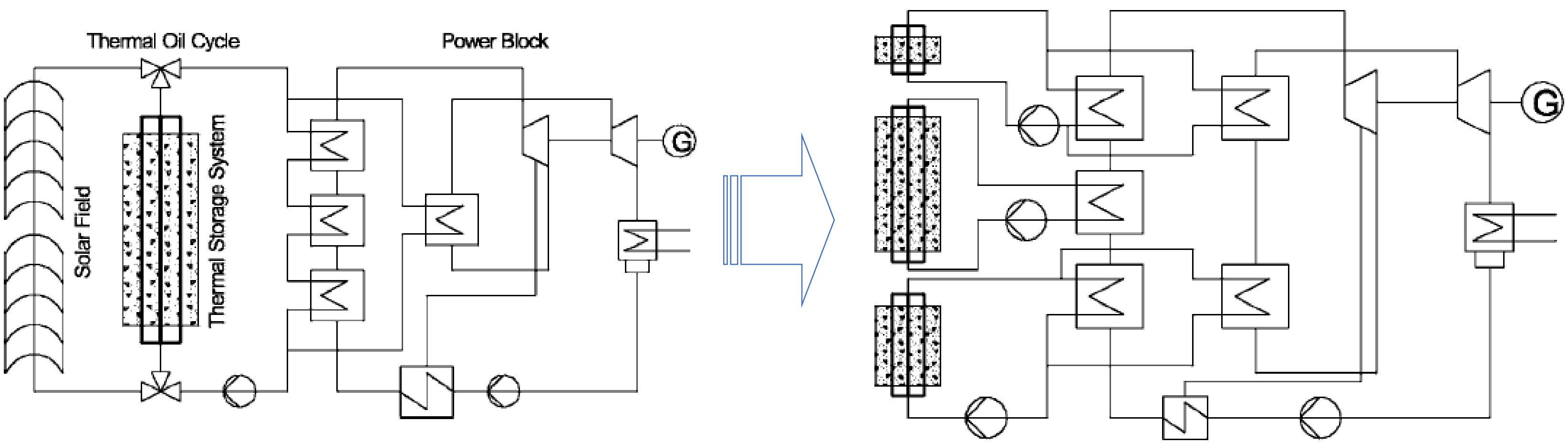
TES for AIR as HTF – other solids (CONCRETE) -2

- **Enhanced Designs**
  - Fins



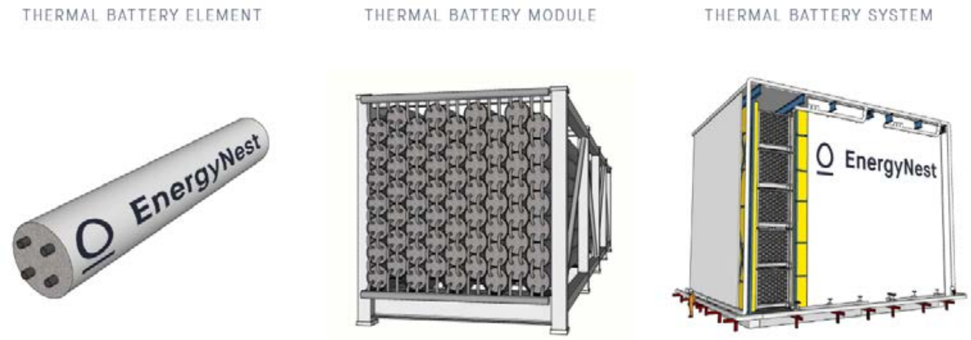


- **Modular systems**



D. Laing et al., 2008, J. Solar Energy Engineering, *V 130.*

TES for AIR as HTF – other solids (CONCRETE) -3

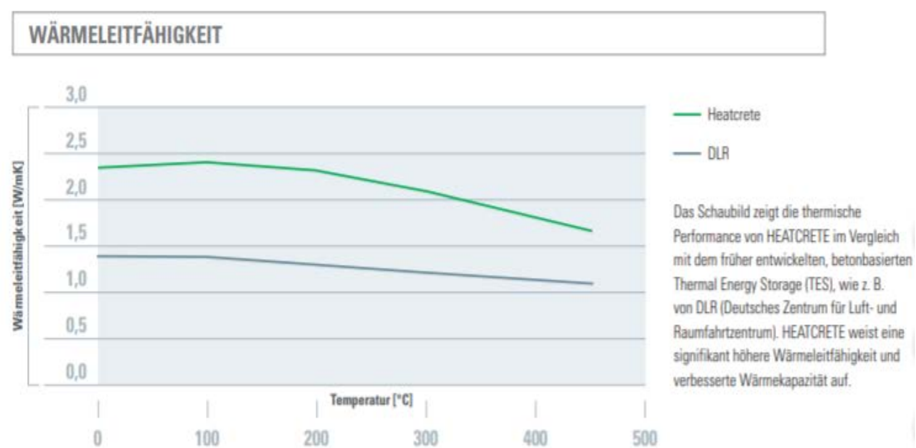


4MWTH storage capacity; 6 hours storage

Tin	550°C
T_{out_Steam}	220°C; 20 bar

Lowest price per KWh stored, $1-2 cents
Modular: From 500KWh to Several GWh

Storage material HEATCRETE®
Guaranteed temperature 450ºC
25 USD/kWh_{th}



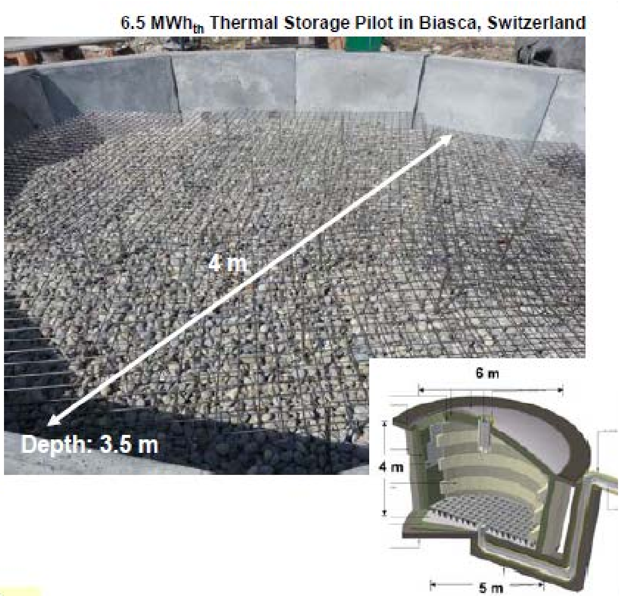
TES for AIR as HTF – other solids (PACKED BEDS)

☺ Direct contact air/storage material

😐 $T_{solid\_filler} \neq T_{Air}$

😐 Air does not work as storage medium

- Natural rocks, pebbles or sand ($\rho Cp \sim 2300$ kJ/m^{3}K)



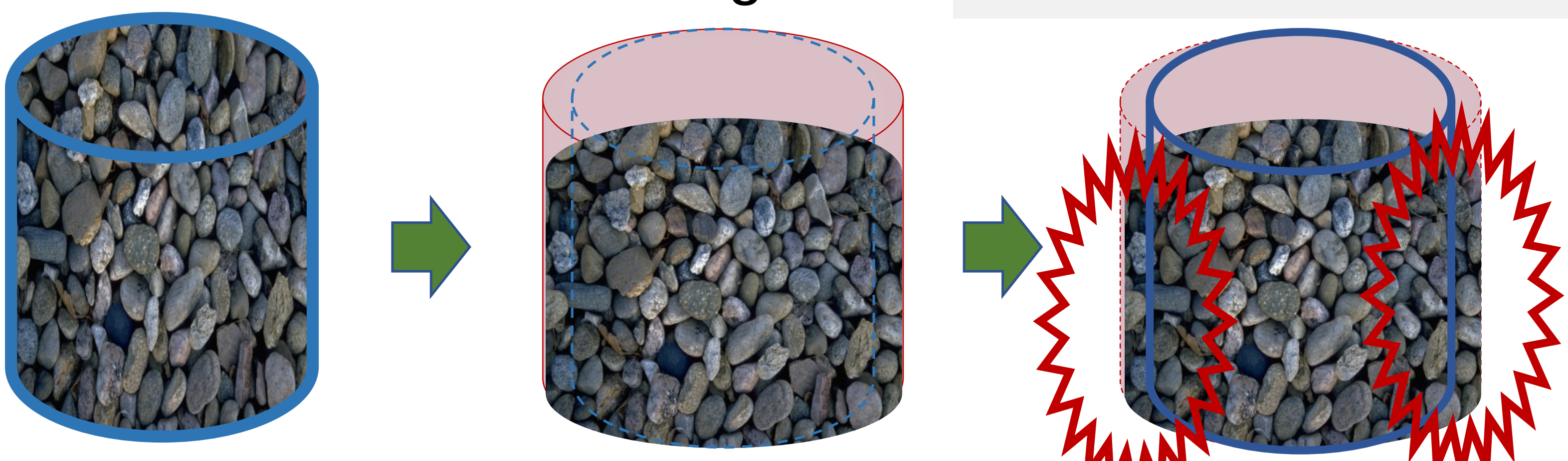
ETES Siemens-Gamesa pilot plant (volcanic rocks; 130MWh)

TES for AIR as HTF – other solids (PACKED BEDS)

potential unfordable mechanical stresses!!!: for the walls and/or the filler

Challenges:

- avoid thermal ratchening



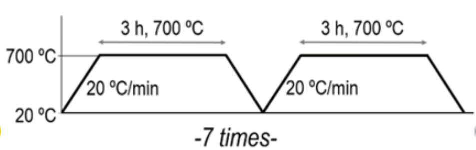
Discharged tank
cold wall tank and filler

Charging tank
thermal walls expansion

Discharging tank
thermal walls contraction

- pebbles degradation

Tested in an electrical oven:
14 heating-cooling cycles



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Tested in ALTAYR:
2 charge-discharge cycles at Tmax =700 ºC

Resuming and Final Remarks

- A holistic approach is need for an appropriate TES design
- Latent storage has a lot of challenges to face, mainly in the range 180-225ºC
- Water storage tanks (sensible storage) is the most use storage (T<100ºC)
- Sensible storage on solids is under development with promising solutions:
  - Regenerative HX at medium temperature
  - Packed beds

….. Many challenges to face!!!.....

Solar Facilities for the European Research Area

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Thank you for your attention

Questions ?

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