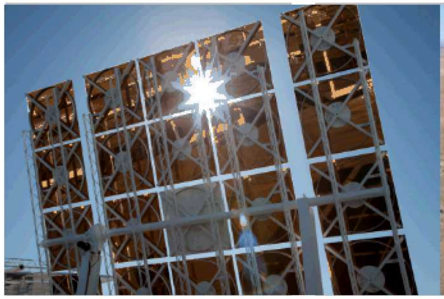
SAND2019-2537C

Designs for Safe and Reliable Thermal Energy Storage



Clifford K. Ho
Sandia National Laboratories
Concentrating Solar Technologies Dept.
Albuquerque, New Mexico
ckho@sandia.gov, (505) 844-2384

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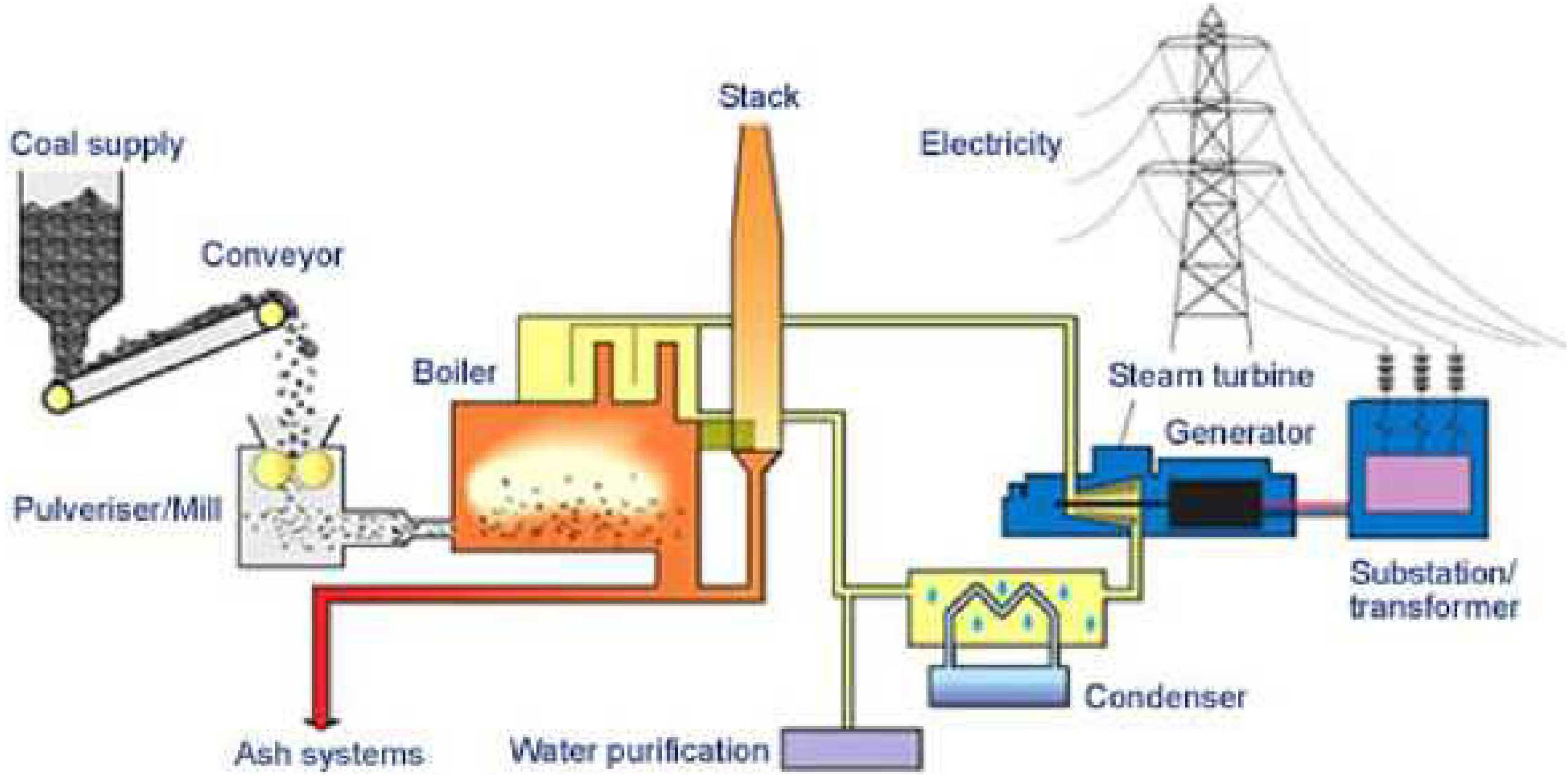
Outline

- Introduction to CSP and Thermal Storage
- Thermal Storage Designs
- Risks and Potential Hazards

What is Concentrating Solar Power (CSP)?

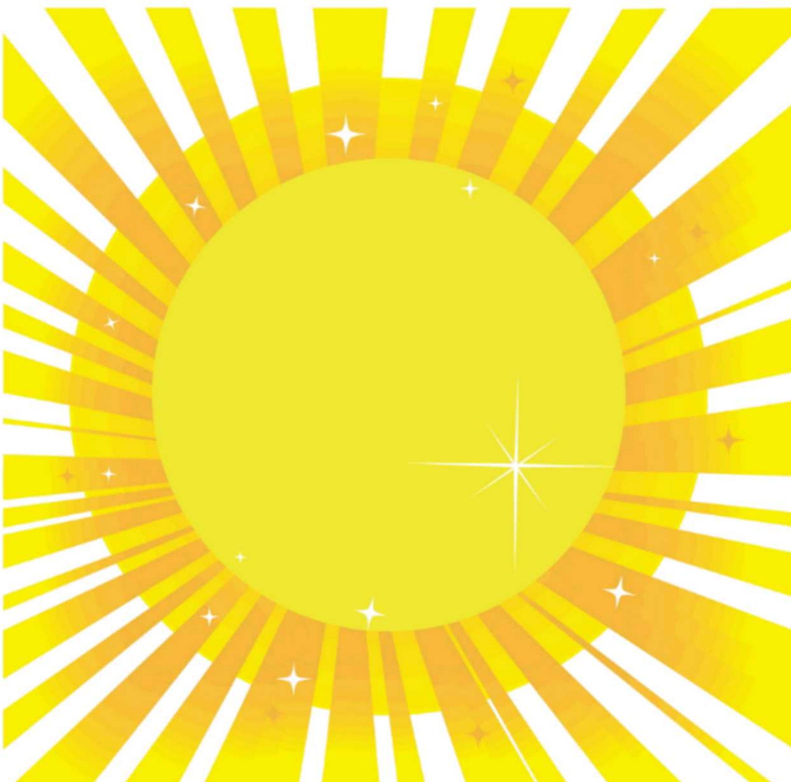
Conventional power plants burn fossil fuels (e.g., coal, natural gas) or use radioactive decay (nuclear power) to generate heat for the power cycle

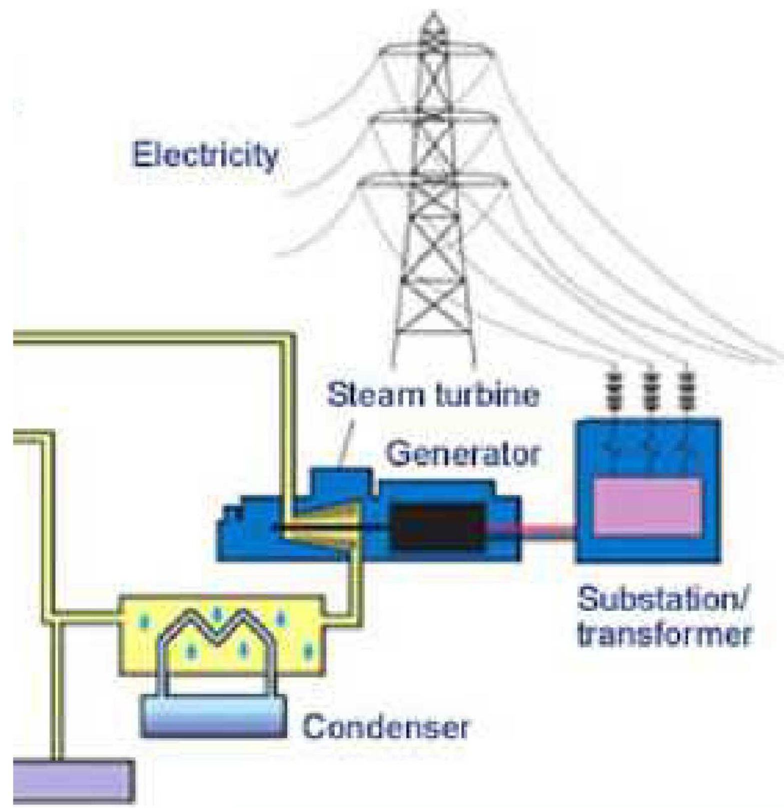


Coal-Fired Power Plant

What is Concentrating Solar Power (CSP)?

CSP uses concentrated heat from the sun as an alternative heat source for the power cycle

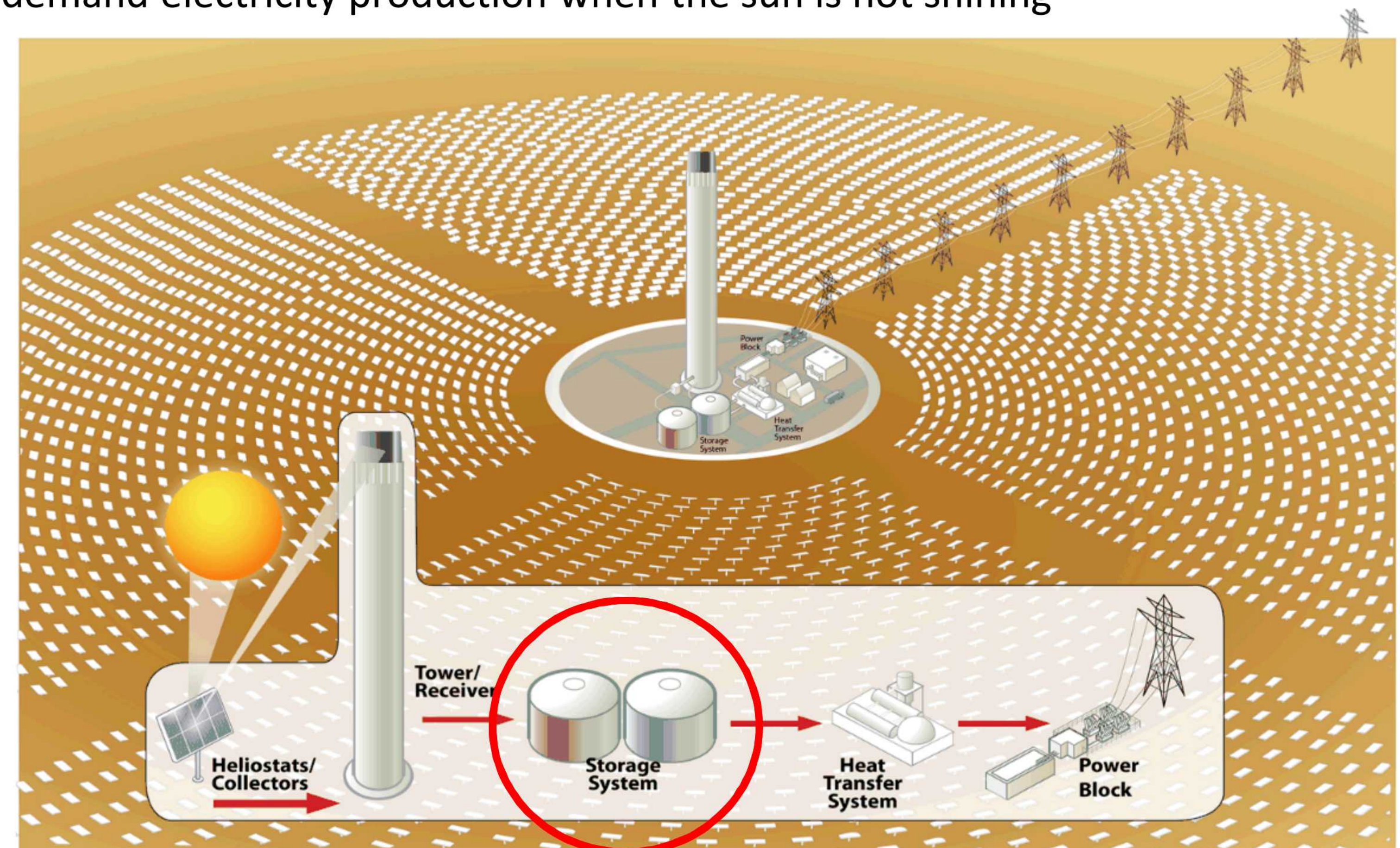




Concentrating Solar Power

CSP and Thermal Energy Storage

- Concentrating solar power uses mirrors to concentrate the sun’s energy onto a receiver to provide heat to spin a turbine/generator to produce electricity
- **Hot fluid can be stored as thermal energy efficiently and inexpensively** for on-demand electricity production when the sun is not shining



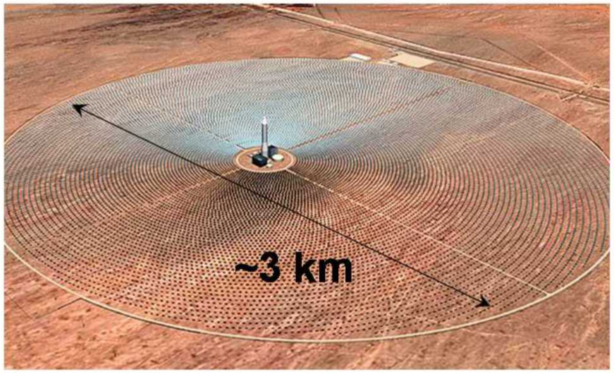
Gemasolar

(near Seville, Spain)

- 1st commercial power tower (19 MW) in the world with 24/7 dispatchable energy production (15 hours of thermal storage using molten salt heated from ~300 – 600 C; ~300 MWh). Commissioned in May 2011.

Crescent Dunes

Tonopah, Nevada



110 MWe power tower near Tonopah, NV. 10 hours of thermal storage (1.1 GWh) using molten nitrate salt heated from ~300 – 600 Commissioned in 2015.

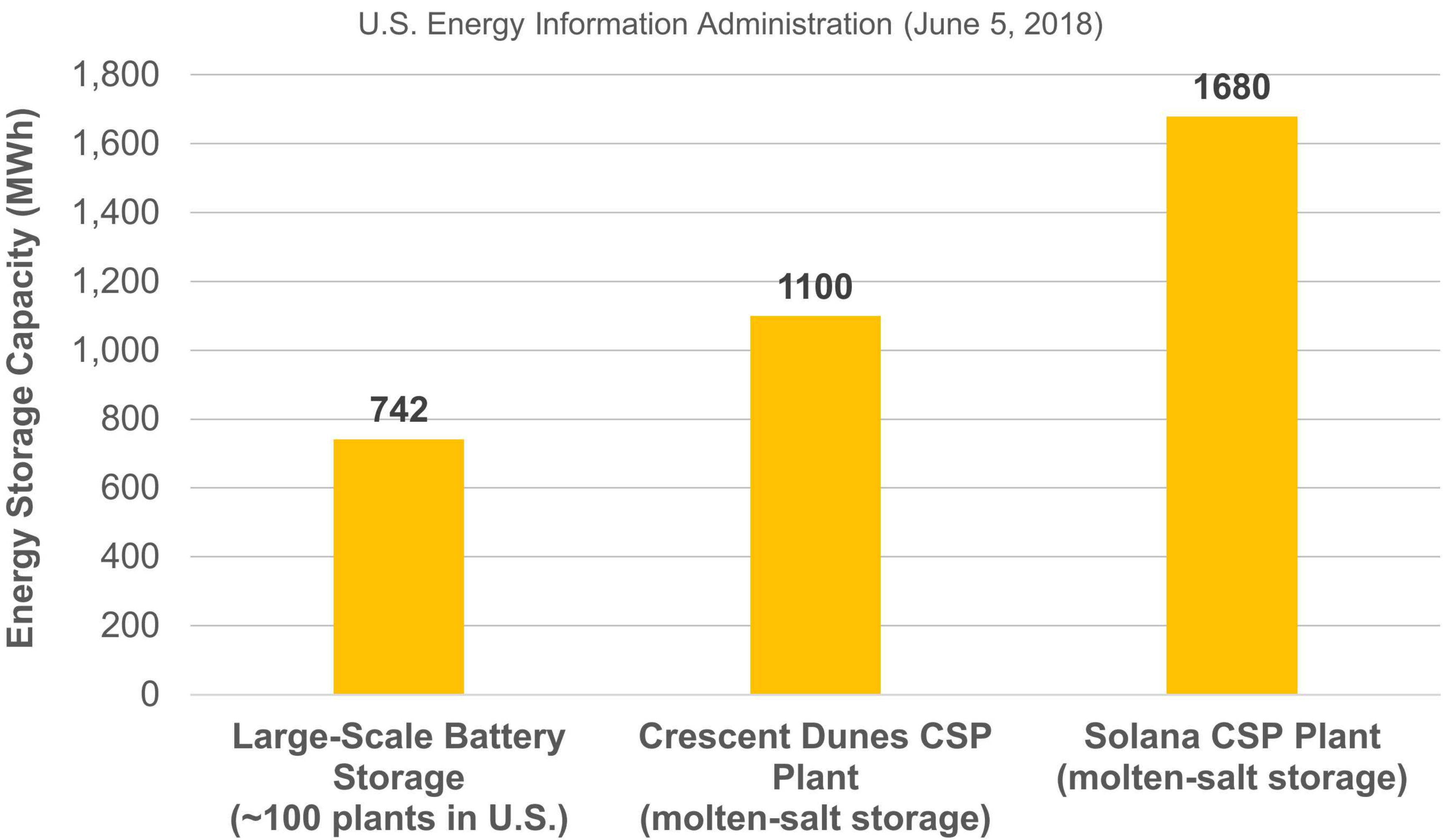
Solana Generating Station

280 MW parabolic trough plant
Phoenix, AZ (Gila Bend)
Started 2013

futurenergyweb.es

6 hours of molten-salt storage heated from ~300 – 400 C (1.7 GWh)

Comparison of Large-Scale Battery and Thermal Energy Storage Capacity in the U.S.



Outline

- Introduction to CSP and Thermal Storage
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Types of Thermal Energy Storage

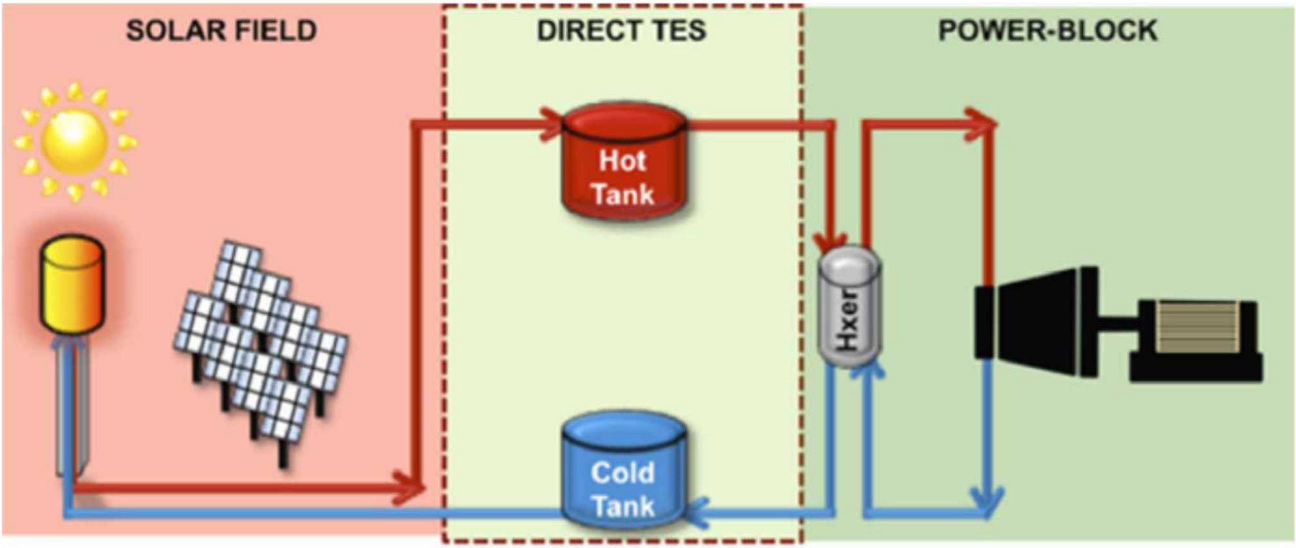
- Sensible (single-phase) storage
  - Use temperature difference to store heat
  - Molten salts (nitrates <600 C; carbonates, chlorides 700 – 900 C)
  - Solids storage (graphite, concrete, ceramic particles), >1000 C
- Phase-change materials
  - Use latent heat to store energy (e.g., molten salts, metallic alloys)
- Thermochemical storage
  - Converting solar energy into chemical bonds to store energy (e.g., decomposition/synthesis, redox reactions)

Molten-salt storage tanks at Solana CSP plant in Arizona. Credit: Abengoa

Falling particles for direct solar heating

Two-Tank Sensible Heat Storage

Lata and Blanco (2010)

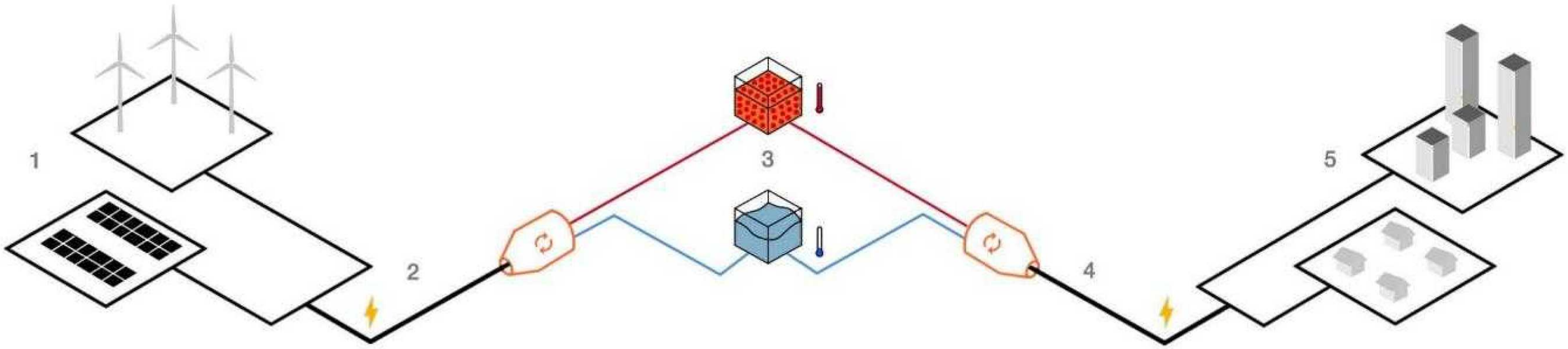


Liu et al. (2016)

$$Q = mc_p \left(T_{hot} - T_{cold} \right)$$

Two-Tank Sensible Heat Storage

"Malta"



1. Collects
Energy is gathered from wind, solar, or fossil generators on the grid as electrical energy and sent to Malta's energy storage system.

2. Converts
The electricity drives a heat pump, which converts electrical energy into thermal energy by creating a temperature difference.

3. Stores
The heat is then stored in molten salt, while the cold is stored in a chilled liquid.

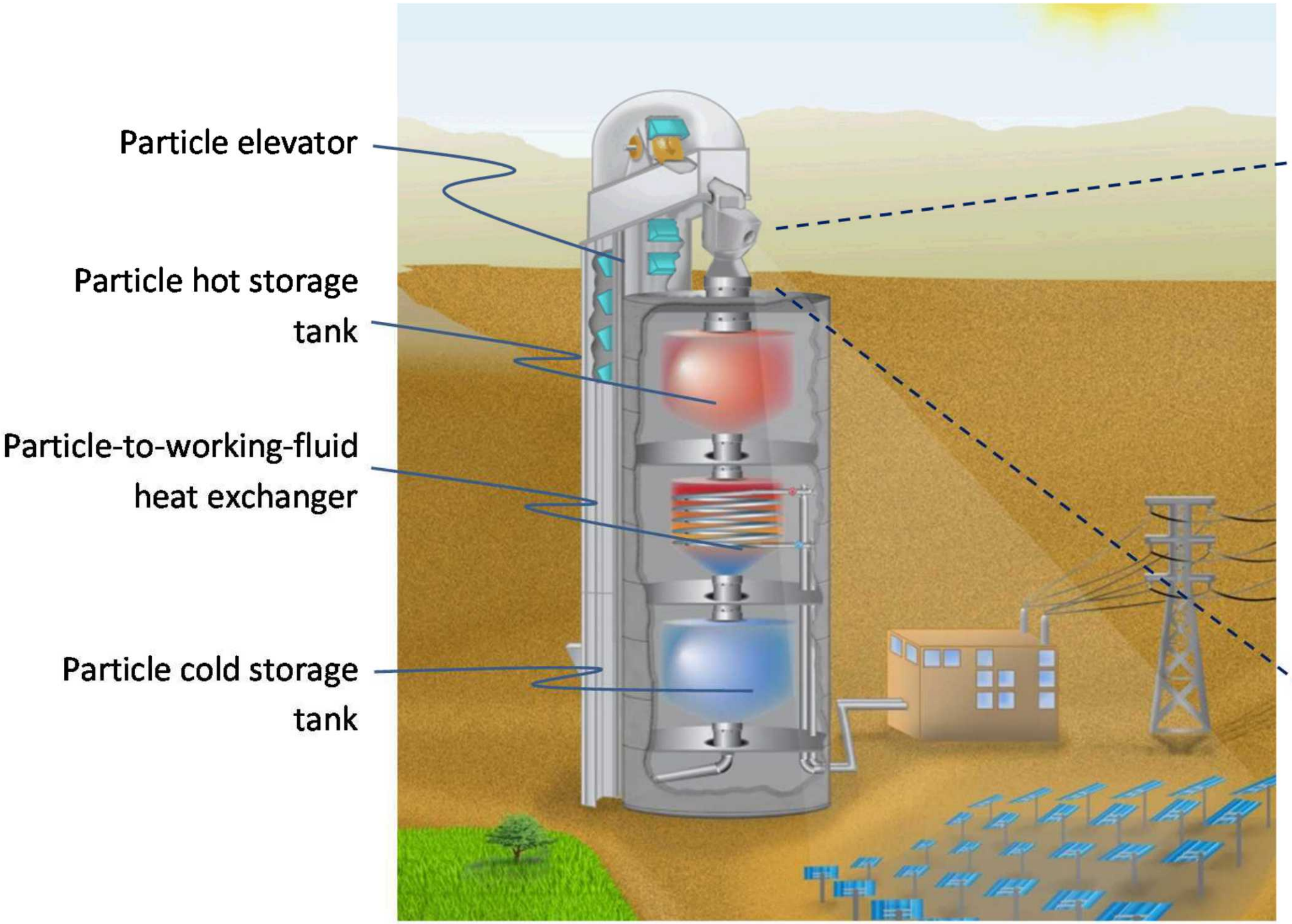
4. Reconverts
The temperature difference is converted back to electrical energy with a heat engine.

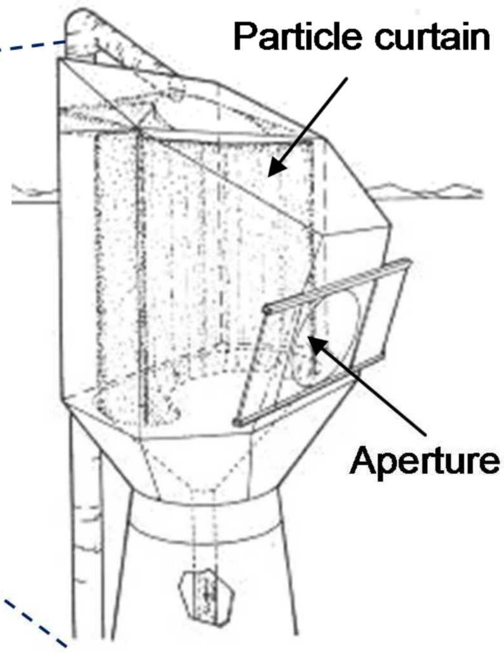
5. Distributes
Electricity is sent back to the grid when it is needed.

Google X

https://x.company/projects/malta/

Two-Tank Particle Storage

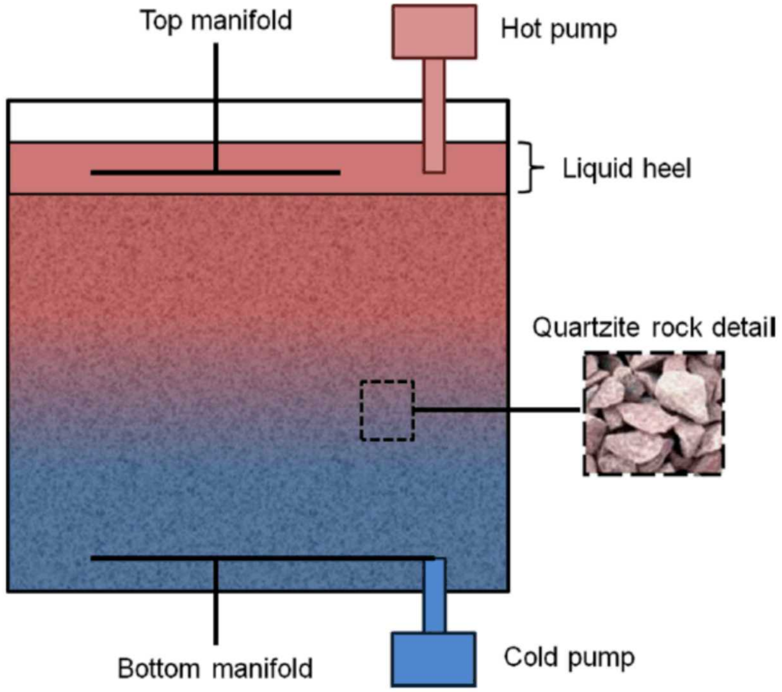


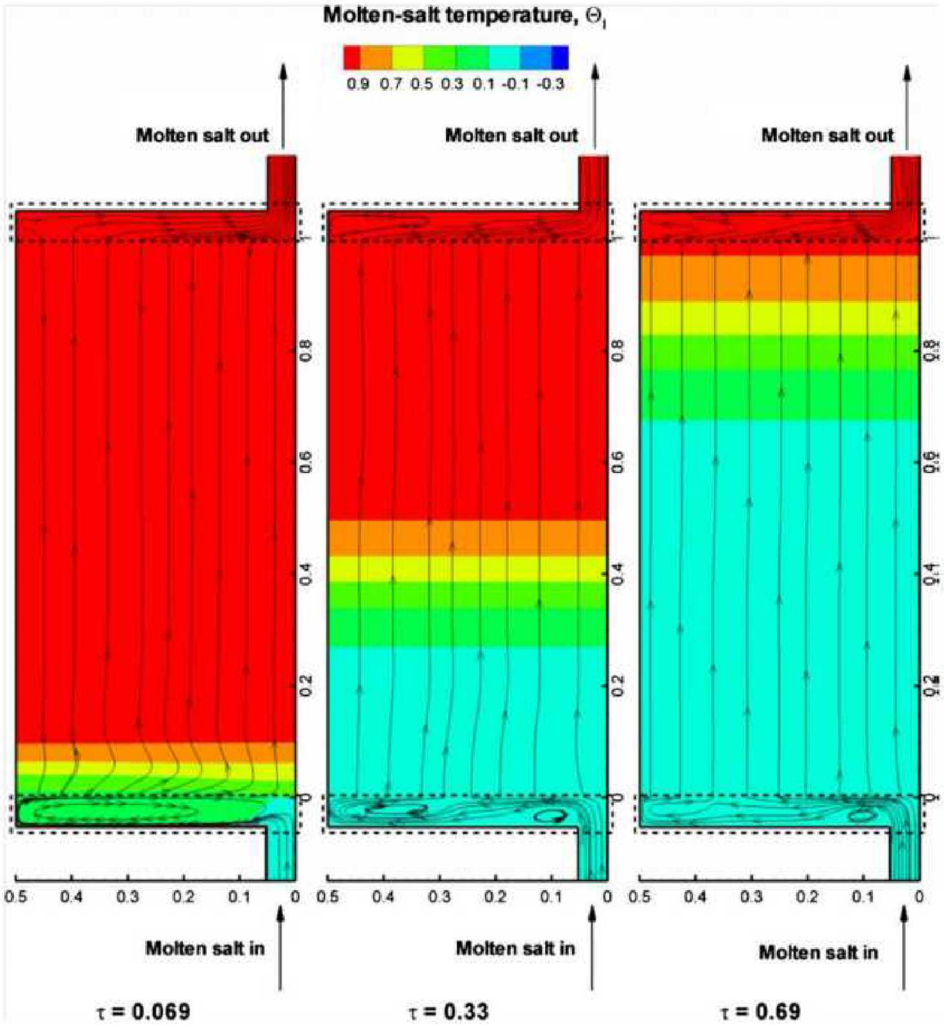


Falling particle receiver

Participants: Sandia, Georgia Tech, Bucknell U., King Saud Univ., DLR

Single-Tank Thermocline Storage





Issues:

- Thermal gradients
- Thermal ratcheting

Outline

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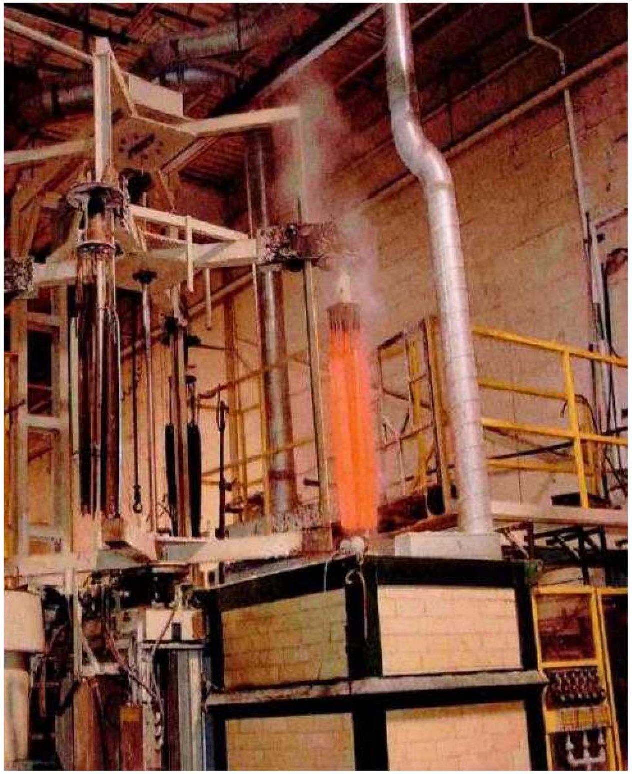
Molten Salt Use in Industry

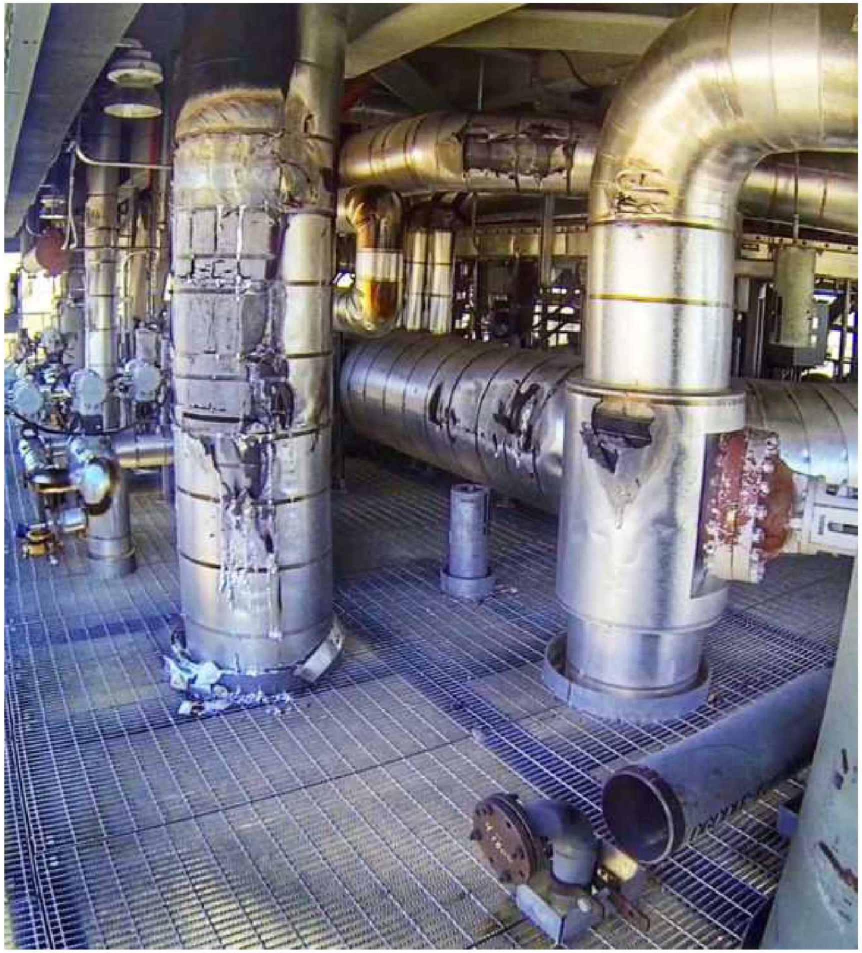
- Molten salt baths have been used in industry for metal treatment for over a century
  - Molten nitrate (200 – 550 C)
  - Molten cyanide (800 – 950 C)
  - Molten chloride (700 C – 1,100 C)
- Well-established safety protocols used in industry
  - Storage
  - Operation / Maintenance
  - Protective clothing and equipment
  - Disposal



Thermal Storage Safety for CSP

- National Fire Protection Agency classifies solar salts (60% sodium nitrate, 40% potassium nitrate) as Class I oxidizers
  - Least hazardous of four classes
  - "an oxidizing material whose primary hazard is that it may increase the burning rate of combustible materials"
- Combustible solids and oxidizable metals should be kept away from molten-salt tanks
  - Use stainless steels or nickel-alloy materials
- Firefighting
  - Carbon dioxide and approved dry powder-type extinguishers should be used – no water of volatile liquids
  - Adequate supply of dry sand should be available for slagging and diking to confine the spread

Risks and Hazards



In May 2016, mirrors that were not tracking properly (human error) caused a small fire in the Unit 3 tower at the Ivanpah concentrating solar power plant, igniting wiring and insulation around pipes

San Bernardino County Fire Department)

Risks and Hazards

Vast Solar 1.1 MW_e liquid sodium concentrating solar plant in Australia.

In 2015, sodium leaked and started a fire beneath the storage tank.

Summary

- Concentrating solar power provides utility-scale electricity *and* energy storage
  - A single CSP plant produces more energy storage than all large-scale battery storage plants in the U.S. as of 2018
- Thermal storage designs
  - Sensible thermal storage (two-tank, thermocline, molten-salt, particles)
  - Latent heat storage (phase change)
  - Thermochemical storage (chemical bonds, reactions)
- Commercial CSP plants in operation with over 10 GWh of thermal energy storage
  - Primary safety concern is leaks and fires
  - No safety incidents of molten nitrate salt storage since 2008
  - No safety incidents of solid media thermal storage

Questions?

Cliff Ho, (505) 844-2384, ckho@sandia.gov

Backup Slides

Comparison of Energy Storage Options

	Energy Storage Technology					
	Solid Particles	Molten Nitrate Salt	Batteries	Pumped Hydro	Compressed Air	Flywheels
Levelized Cost[1] ($/MWh$_e$)	10 – 13	11 – 17	100 – 1,000	150 - 220	120 – 210	350 - 400
Round-trip efficiency[2]	>98% thermal storage ~40% thermal-to-electric	>98% thermal storage ~40% thermal-to-electric	60 – 90%	65 – 80%	40 – 70%	80 – 90%
Cycle life[3]	>10,000	>10,000	1000 – 5000	>10,000	>10,000	>10,000
Toxicity/ environmental impacts	N/A	Reactive with piping materials	Heavy metals pose environmental and health concerns	Water evaporation/ consumption	N/A	N/A
Restrictions/ limitations	Particle/fluid heat transfer can be challenging	< 600 °C (decomposes above ~600 °C)	Very expensive for utility-scale storage	Large amounts of water required	Unique geography required	Only provides seconds to minutes of storage

TABLE 1 | The Physical Properties of Selected Thermal Energy Storage Media. Sensible Energy Storage Media, Both Liquid and Solid, Are Assumed to Have a Storage Temperature Differential of 350°C with Respect to the Calculation of Volumetric and Gravimetric Storage Density

Storage Medium	Specific Heat (kJ/kg-K)	Latent or Reaction Heat (kJ/kg)	Density (kg/m^3)	Temperature Range (°C) Cold	Hot	Gravimetric Storage Density (kJ/kg)	Volumetry Storage Density (MJ/m^3)	References
Sensible Energy Storage—Solids								
Concrete	0.9	–	2200	200	400	315	693	23
Sintered bauxite particles	1.1	–	2000	400	1000	385	770	24
NaCl	0.9	–	2160	200	500	315	680	23
Cast iron	0.6	–	7200	200	400	210	1512	25
Cast steel	0.6	–	7800	200	700	210	1638	23
Silica fire bricks	1	–	1820	200	700	350	637	23
Magnesia fire bricks	1.2	–	3000	200	1200	420	1260	25
Graphite	1.9	–	1700	500	850	665	1131	26
Aluminum oxide	1.3	–	4000	200	700	455	1820	27
Slag	0.84	–	2700	200	700	294	794	28
Sensible Energy Storage—Liquids								
Nitrate salts (ex. KNO_3-0.46$NaNO_3$)	1.6	–	1815	300	600	560	1016	17
Therminol VP-1®	2.5	–	750	300	400	875	656	29
Silicone oil	2.1	–	900	300	400	735	662	23
Carbonate salts	1.8	–	2100	450	850	630	1323	23
Caloria HT-43®	2.8	–	690	150	316	980	676	25
Sodium liquid metal	1.3	–	960	316	700	455	437	25
Na-0.79K metal eutectic	1.1	–	900	300	700	385	347	30
Hydroxide salts (ex. NaOH)	2.1	–	1700	350	1100	735	1250	27
Latent Energy Storage								
Aluminum	1.2	397	2380	–	660	397	945	28
Aluminum alloys (ex. Al-0.13Si)	1.5	515	2250	–	579	515	1159	31, 32
Copper alloys (ex. Cu-0.29Si)	–	196	7090	–	803	196	1390	32
Carbonate salts (ex. Li_2CO_3)	–	607	2200	–	726	607	1335	32
Nitrate salts (ex. KNO_3-0.46$NaNO_3$)	1.5	100	1950	–	222	100	195	28
Bromide salts (ex. KBr)	0.53	215	2400	–	730	215	516	33
Chloride salts (ex. NaCl)	1.1	481	2170	–	801	481	1044	33
Flouride salts (ex. LiF)	2.4	1044	2200	–	842	1044	2297	33
Lithium hydride	8.04	2582	790	–	683	2582	2040	31
Hydroxide salts (ex. NaOH)	1.47	160	2070	–	320	160	331	31
Thermochemical Energy Storage								
$SO_3(g) \leftrightarrow SO_2(s) + 1/2O_2(g)$	–	1225	–	–	650	1225	–	28, 30, 34
$CaCO_3(s) \leftrightarrow CO_2(g) + CaO(s)$	–	1757	–	–	527	1757	–	28, 34
$CH_4(g) + CO_2(g) \leftrightarrow 2CO(g) + 2H_2(g)$	–	4100	–	–	538	4100	–	35
$CH_4(g) + H_2O(g) \leftrightarrow 3H_2(g) + CO(g)$	–	6064	–	–	538	6064	–	35
$Ca(OH)_2(s) \leftrightarrow CaO(s) + H_2O(g)$	–	1351	–	–	521	1351	–	28, 30, 34
$NH_3(g) \leftrightarrow 1/2N_2(g) + 3/2H_2(g)$	–	3900	–	–	195	3900	–	36

Siegel (2012)

Thermal Energy Storage Goals

- Capable of achieving high temperatures (> 700 C)
- High energy and exergetic efficiency (>95%)
- Large energy density (MJ/m^3)
- Low cost (<$15/$kWh_t$; <$0.06/kWh_e for entire CSP system)
- Durable (30 year lifetime)
- Ease of heat exchange with working fluid ($h > 100\ W/m^2\text{-}K$)

Solid-based (graphite) central-receiver system at Lake Cargelligo, NSW, Australia

- Graphite block is heated in face-down receiver
- Used to heat steam from 200 C to 500 C
  - Powers a 3 MW_e steam-Rankine cycle.