High-Temperature Particle-Based CSP with Thermal Storage

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Sandia National Laboratories

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SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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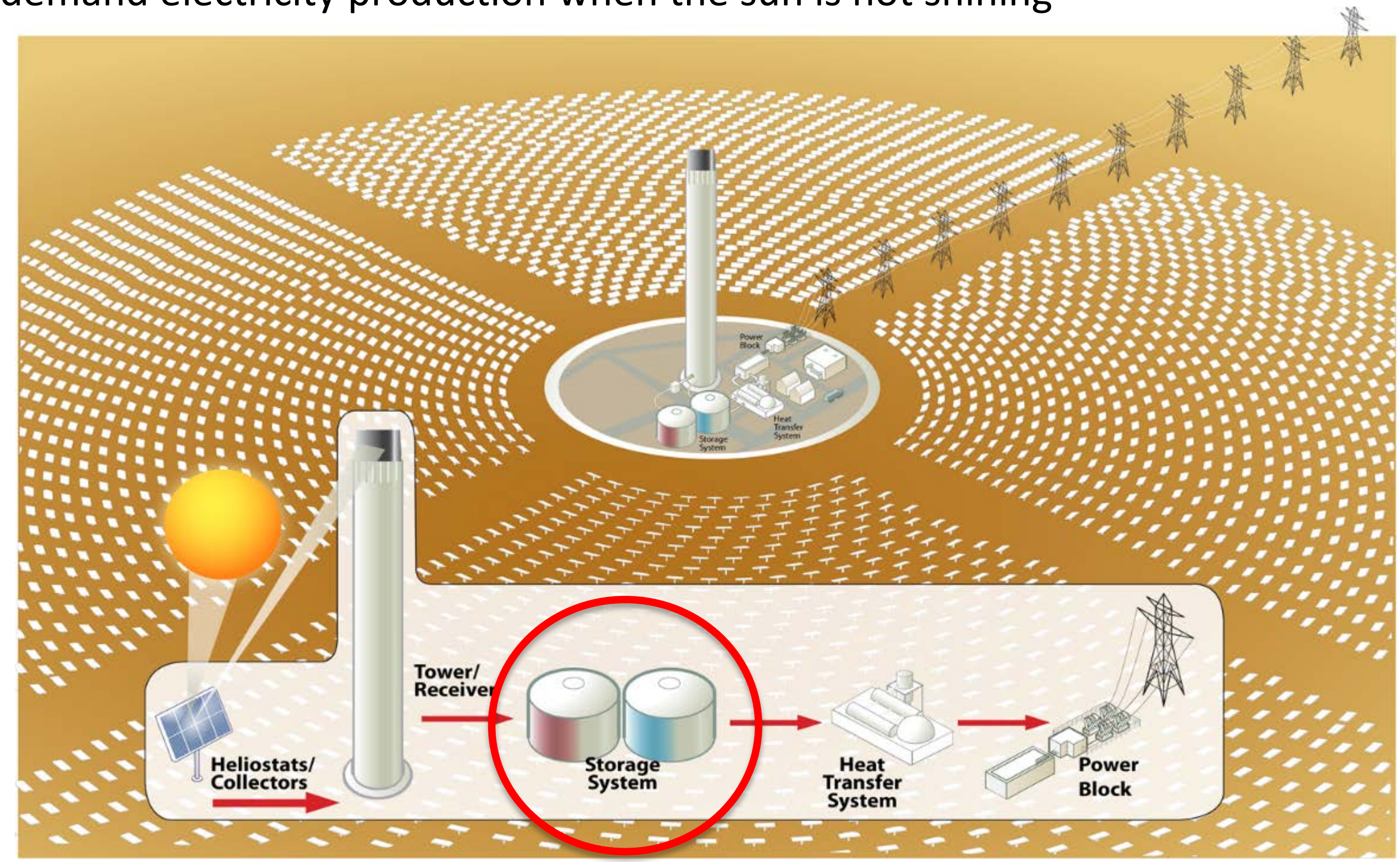
Overview

- Introduction
- Particle-Based CSP
- High Temperature Particle Storage
- Conclusions

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



DOE Gen 3 CSP Program

- Higher operating temperatures
  - Higher efficiency electricity production
    - Supercritical CO_2 Brayton Cycles (>700 ˚C)
    - Air Brayton Combined Cycles (>1000 ˚C)
  - Thermochemical storage & solar fuel production (>1000 ˚C)

→ Particle-based CSP systems with high-temperature storage

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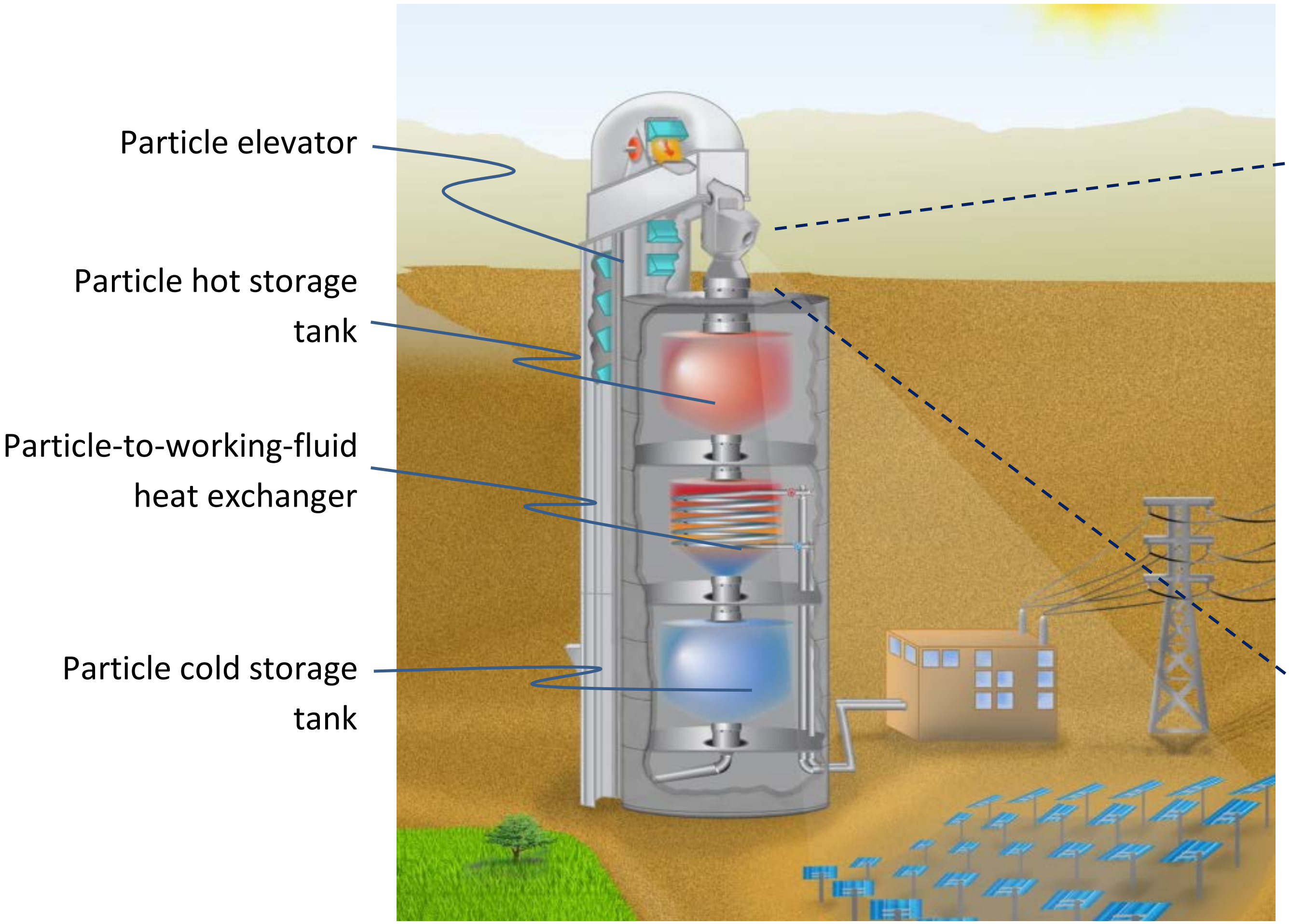
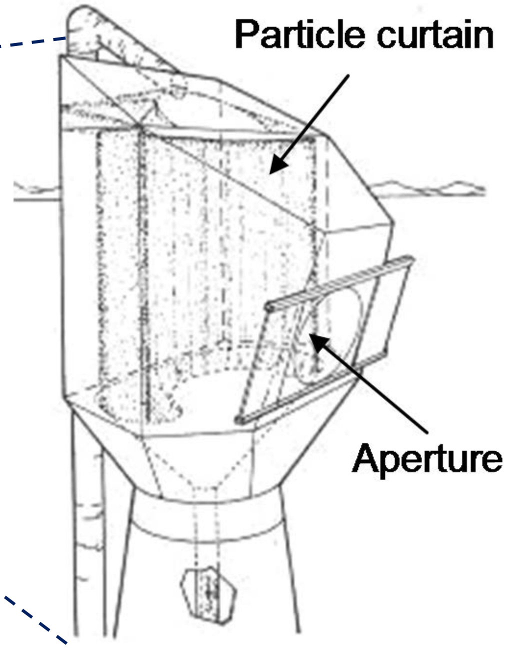
High Temperature Falling Particle Receiver





Falling particle receiver

Goal: Achieve higher temperatures, higher efficiencies, and lower costs

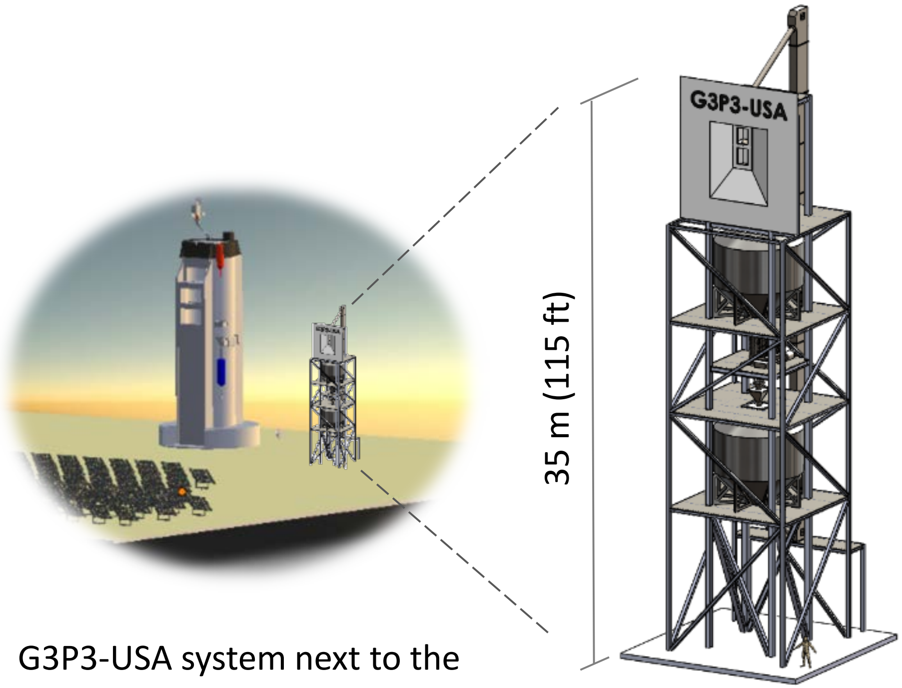
Particle Receiver Designs – Free Falling

Value Proposition

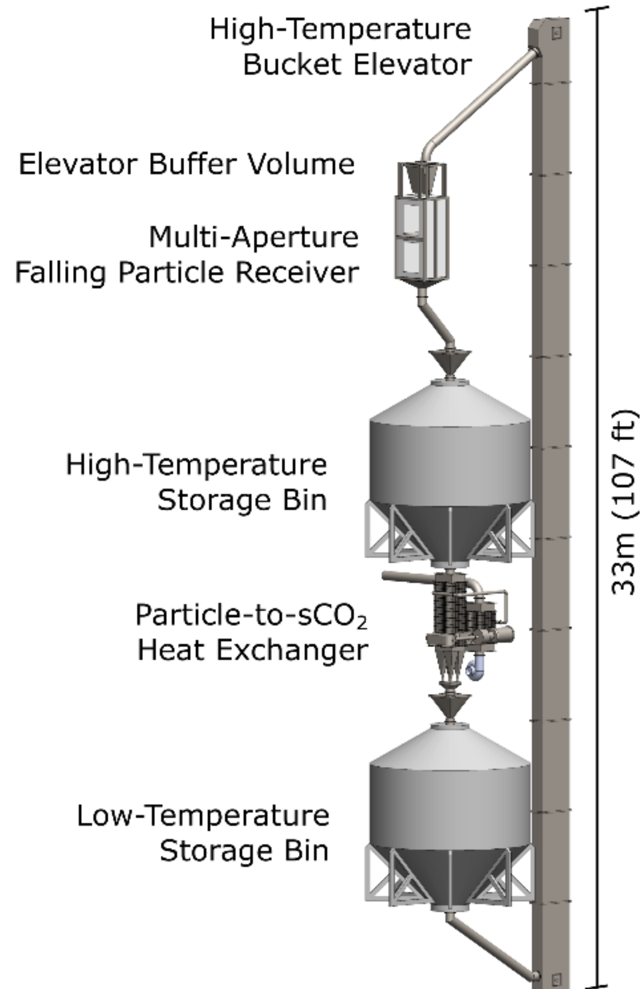
- Proposed particle receiver system has significant advantages over current state-of-the-art CSP systems
  - Sub-zero to over ~1000 °C operating temperatures
  - No freezing and need for expensive trace heating
  - Use of inert, non-corrosive, inexpensive materials
  - Direct storage (no need for additional heat exchanger)
  - Direct heating of particles (no flux limitations on tubes; immediate temperature response)

Gen 3 Particle Pilot Plant (G3P3)

Integrated System



G3P3-USA system next to the existing 200-ft tower at the National Solar Thermal Test Facility Sandia National Laboratories, Albuquerque, NM



Baseline Design

Overview

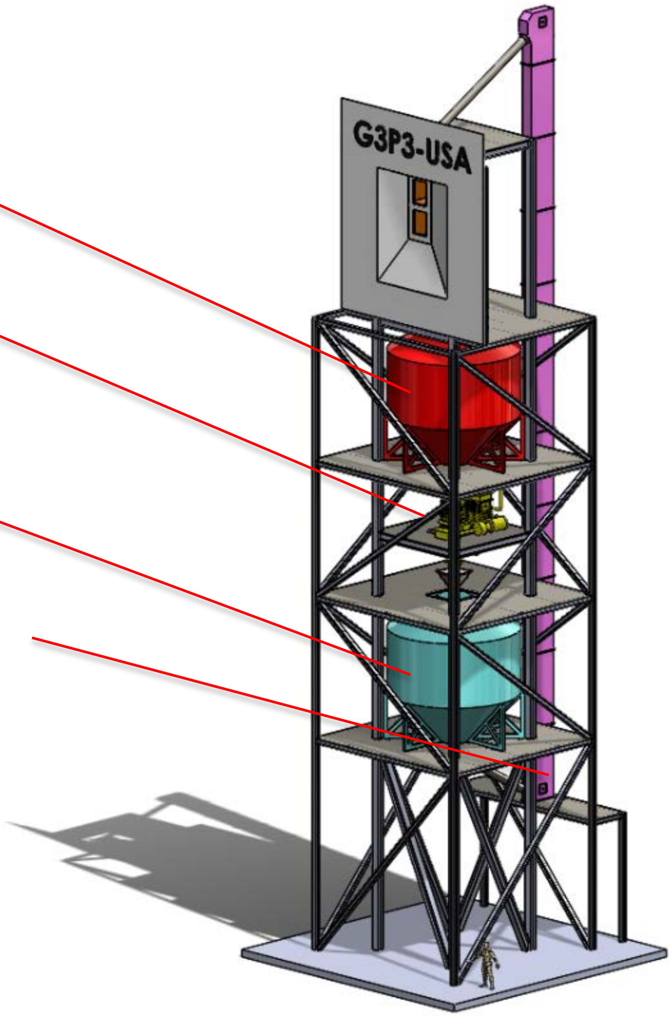
- Introduction
- Particle-Based CSP
- High Temperature Particle Storage
- Conclusions

Particle Storage Considerations

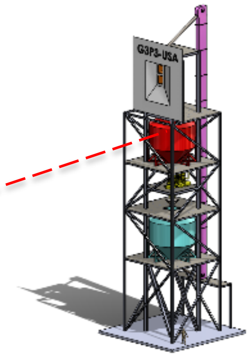
- Configuration
  - Two-tank vs. Single-tank thermocline
- Sizing and shape
  - Energy storage capacity
  - Shape: heat loss vs. stress
- Particle Materials
  - Engineered vs. natural materials
- Cost
  - Levelized cost of storage options

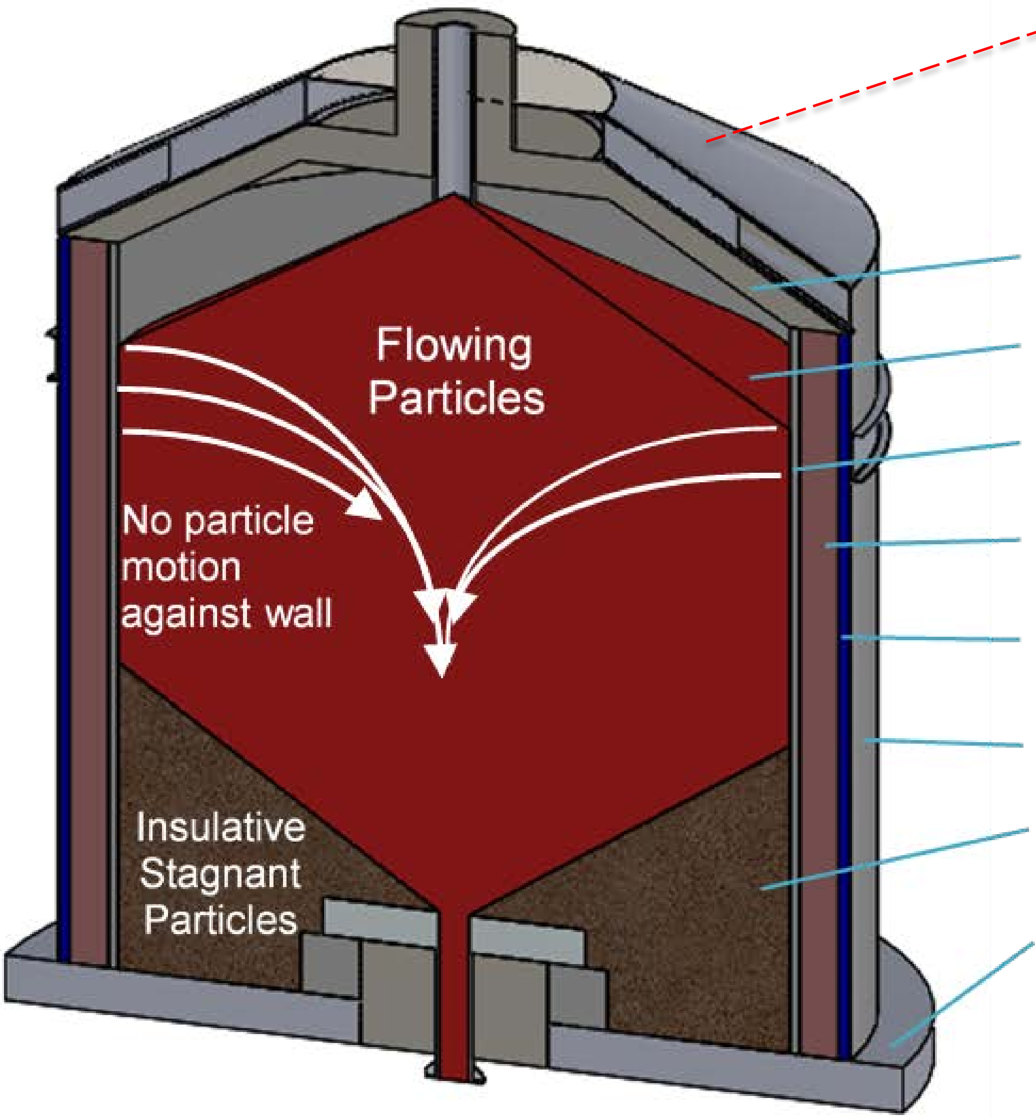
Two-Tank Particle Storage

- Hot Particle Storage
- Particle Heat Exchanger
- Cold Particle Storage
- Particle Lift and Conveyance



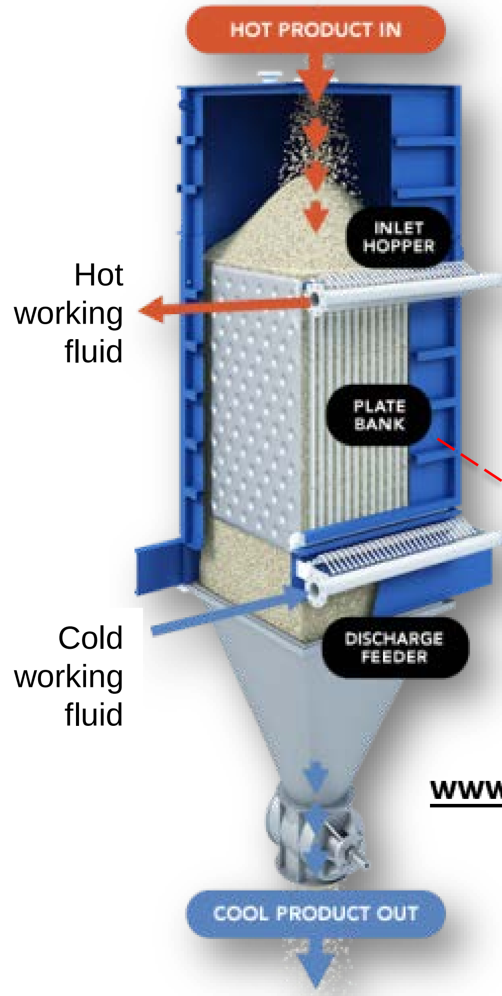
Two-Tank Storage Design

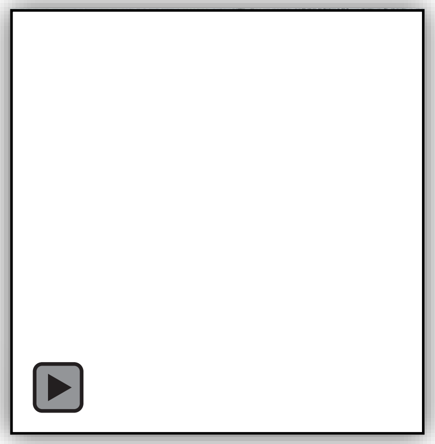




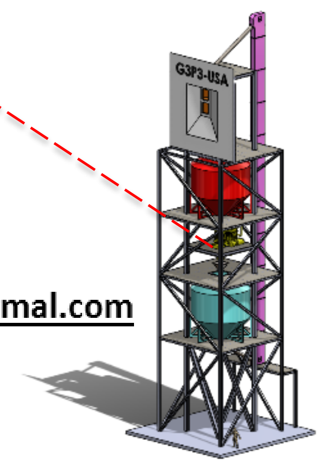
Particle Heat Exchanger
(for Two-Tank storage)

Type	Pros	Cons
Fluidized Bed	High heat-transfer coefficients	Energy and mass loss from fluidization
Moving packed bed	Gravity-fed particle flow; low erosion	Low particle-side heat transfer



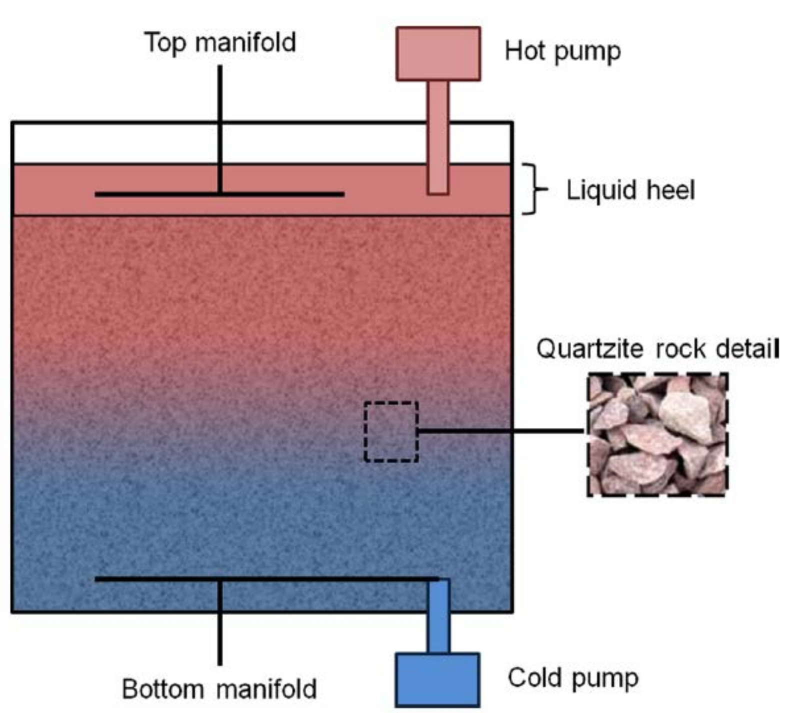


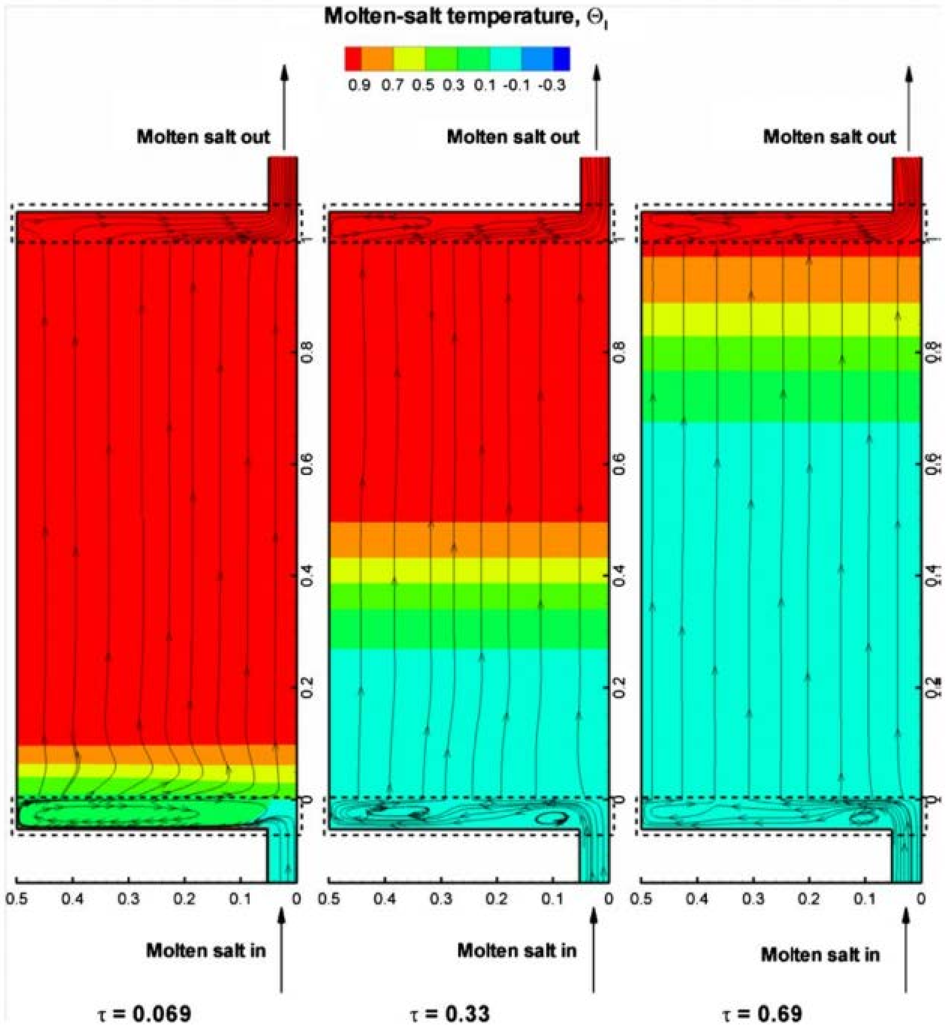
www.cpfd-software.com



www.solexthermal.com

Single-Tank Thermocline Storage





Issues:

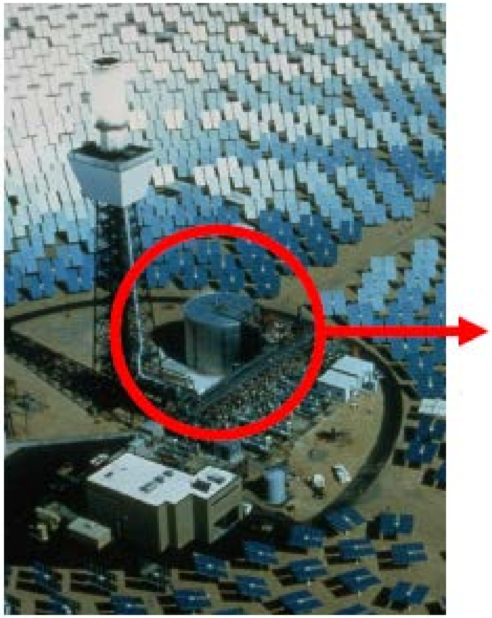
- Thermal gradients
- Thermal ratcheting

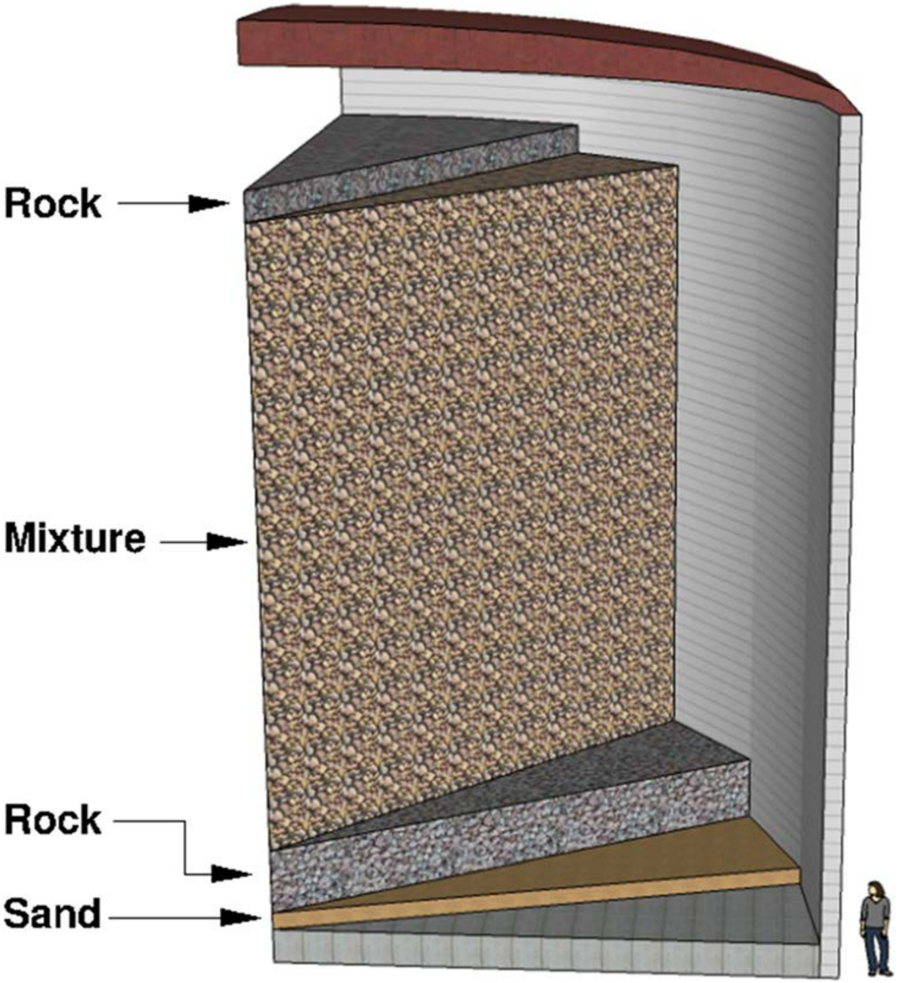
Fluekiger et al. (2013, 2014)

Solar One Thermocline Test (1982-1986)

Faas et al., SAND86-8212

- 300 °C, 182 MWh_t, oil HTF, sand/gravel, 13 m tall, H/D=0.66

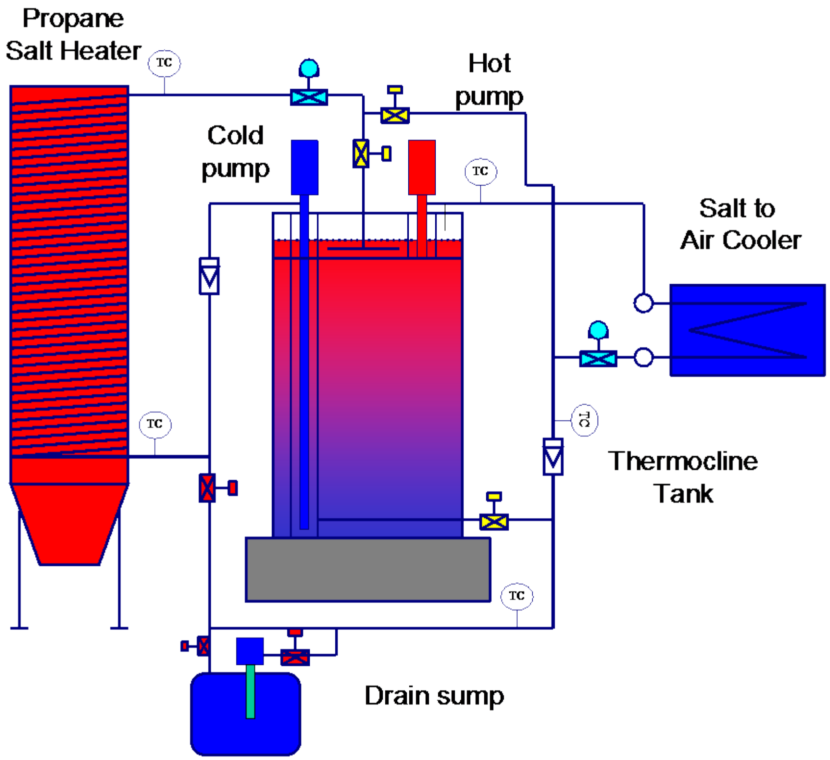




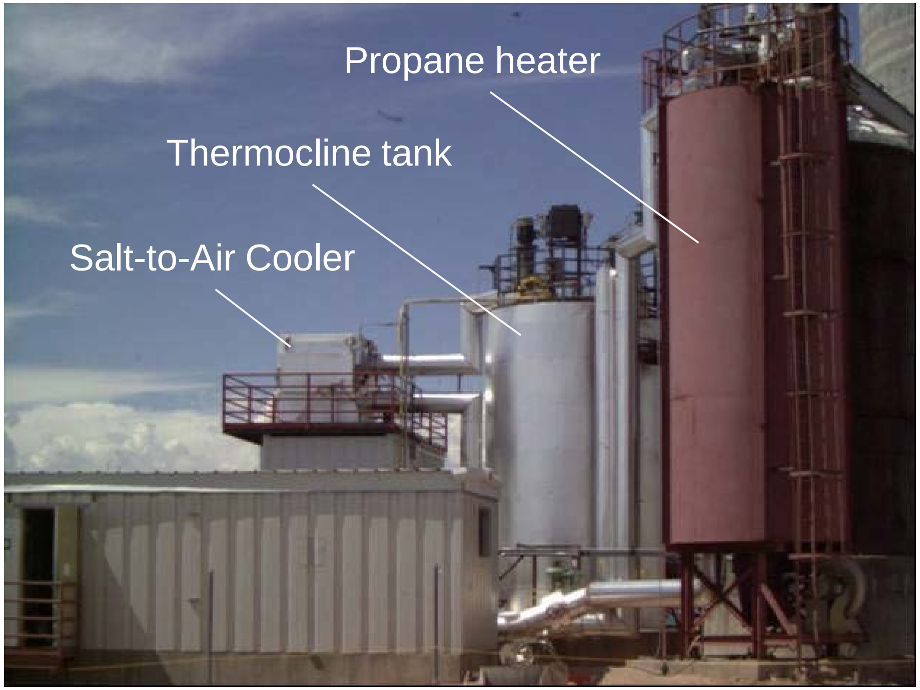
Fluekiger et al. (2012)

Sandia Thermocline Test (2001)

- 400 °C, 2.3 MWh_t, salt HTF, sand/gravel, 6.1 m tall, H/D = 2.0



Pacheco et al., JSEE, 2002



Brosseau et al., SAND2004-3207

Configuration Findings

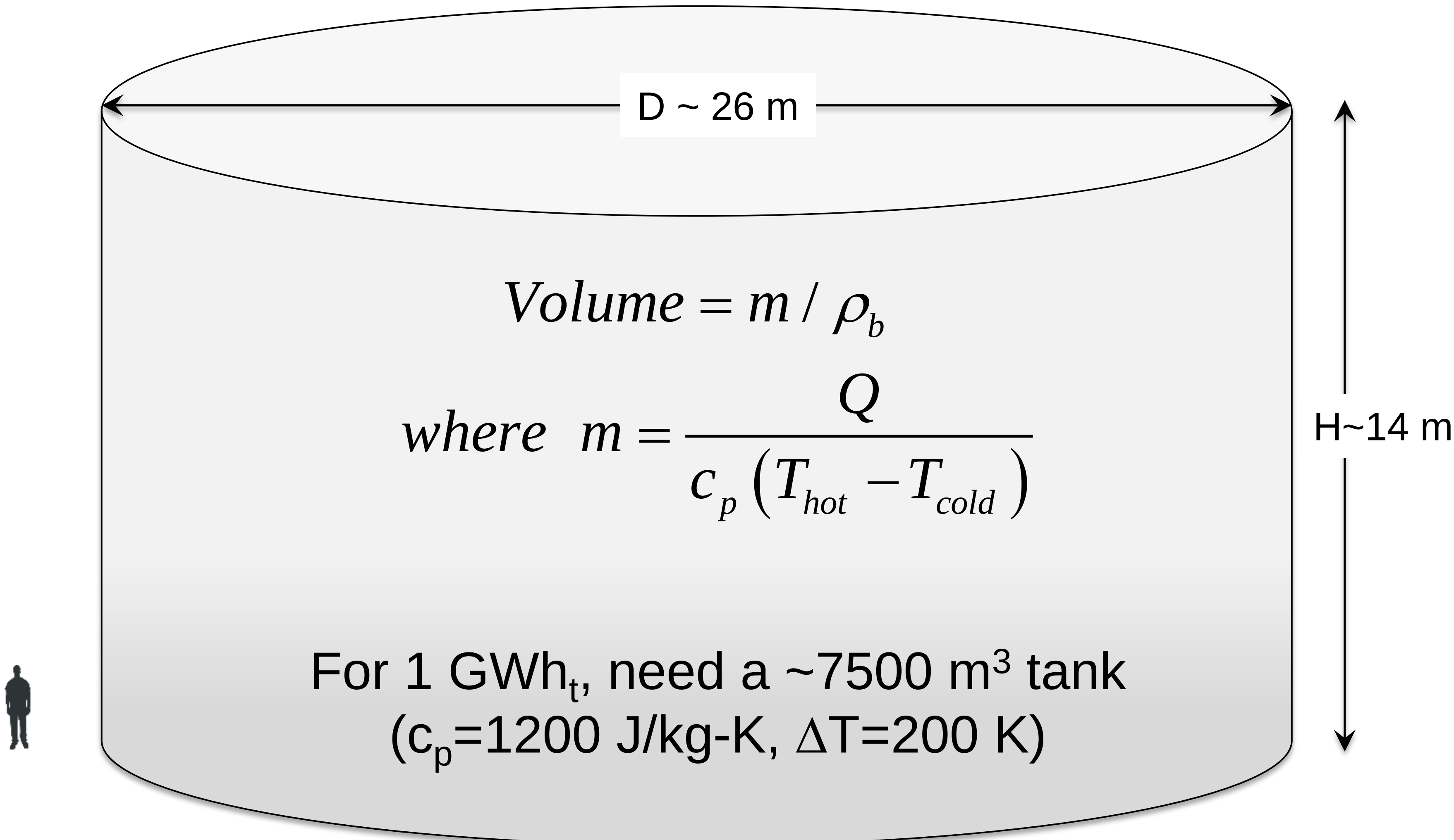
Thermocline Storage

- Heat-transfer fluid flows across a bed of particles for charging and discharging
- Single tank may reduce materials and cost by 30%
- Thermal ratcheting may cause tank damage
- Diffuse temperature profile reduces performance
- Quartzite rock and silica sand worked well with molten salt

Two-Tank Storage

- Particles are heated first and then stored in hot tank
- Requires particle conveyance to tanks and heat exchanger(s)
- Requires particle-to-working fluid heat exchanger
  - Gravity-driven moving packed bed
  - Fluidized bed

Tank Sizing



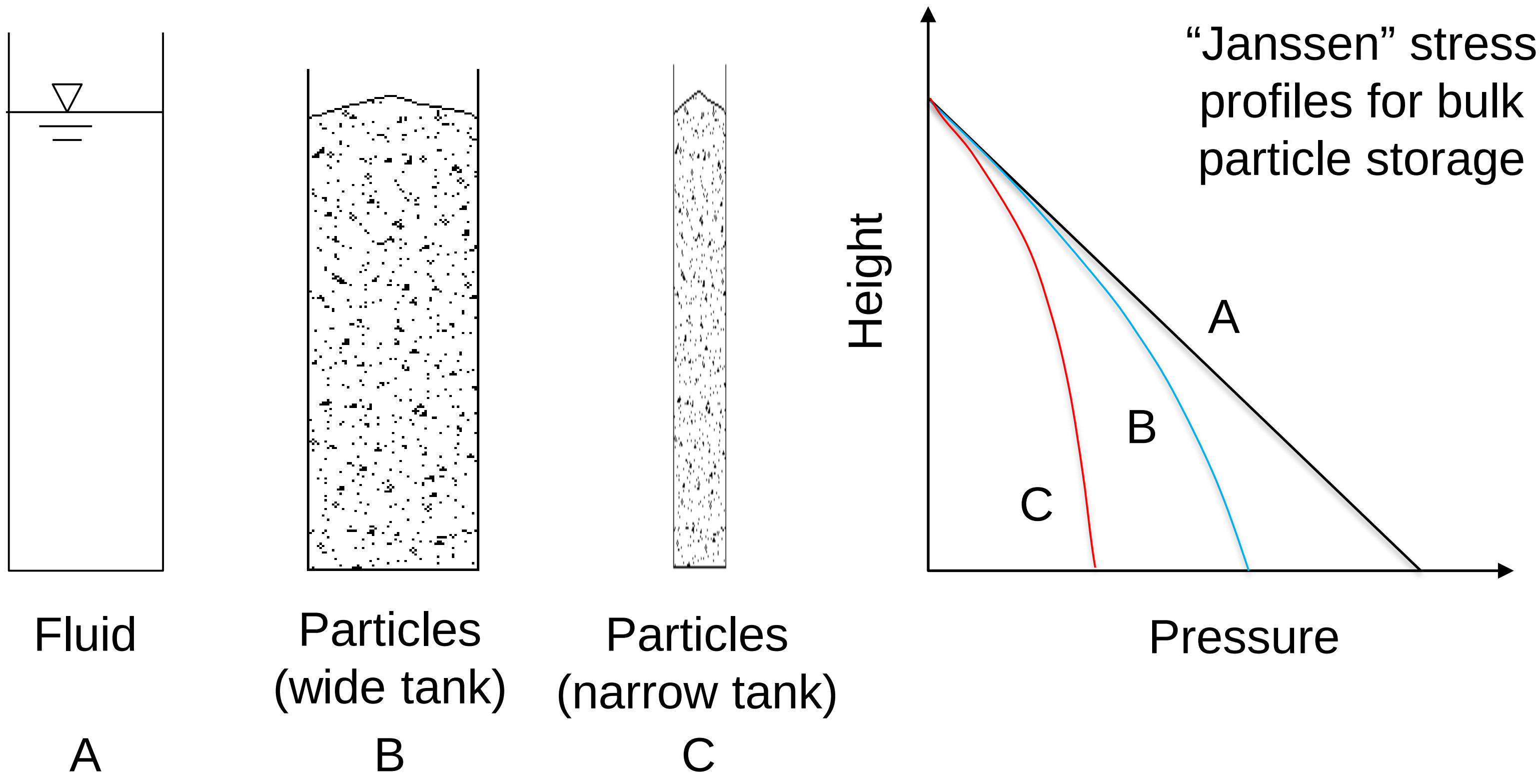
$$Volume = m / \rho_b$$

$$where \quad m = \frac{Q}{c_p \left(T_{hot} - T_{cold}\right)}$$

For 1 GWh_t, need a ~7500 m^3 tank
(c_p=1200 J/kg-K, ΔT=200 K)

Tank Shape

- Consideration of heat loss and wall stresses



Tank Shape

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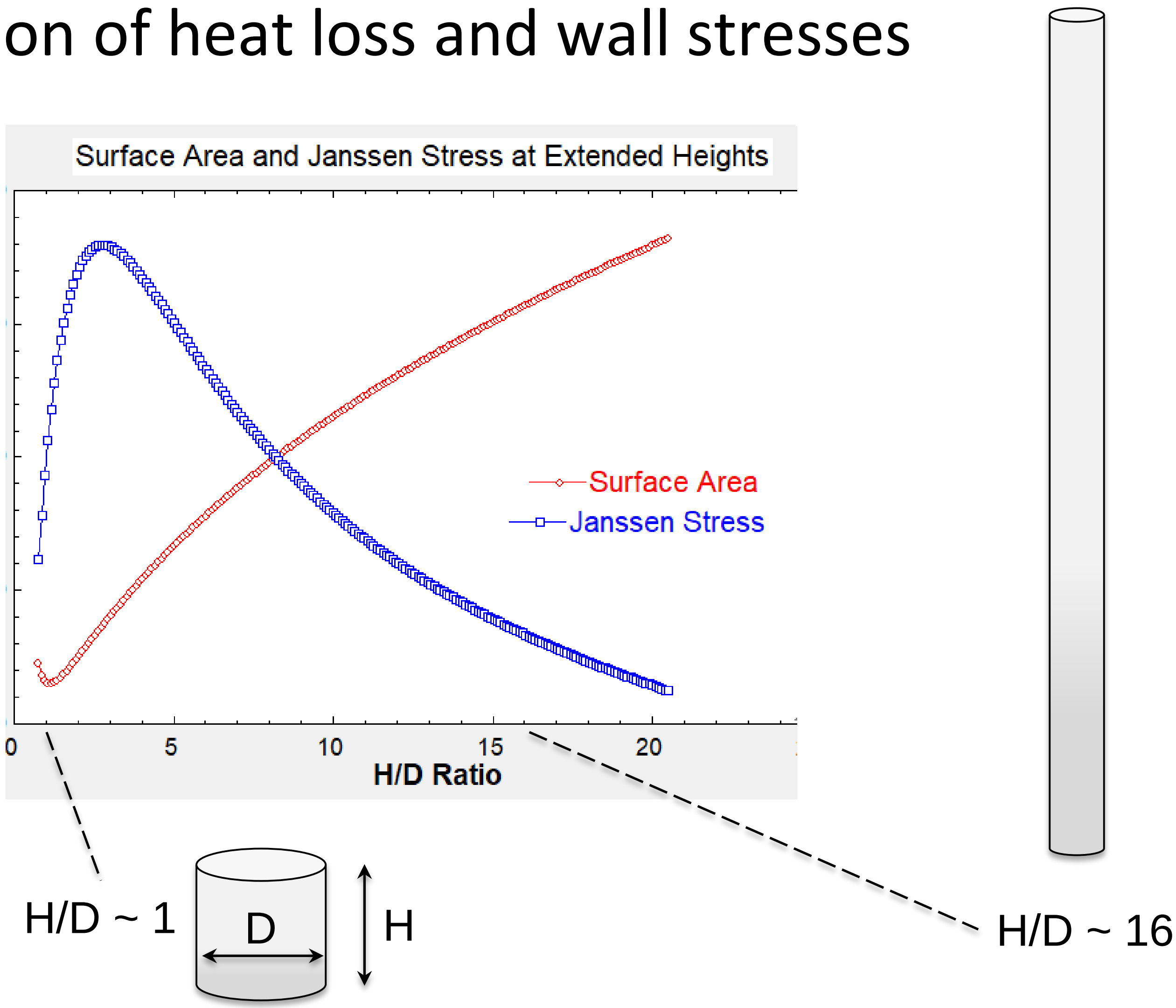


Particle Materials

- Thermocline storage
  - High heat capacity
  - Low void fraction
  - Low cost
  - Brosseau et al. (SAND2004-3207)

Quartzite rock

Silica Sand

Siegel, Wiley, (2012)

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

Particle Materials

Cost of particle materials (delivered)

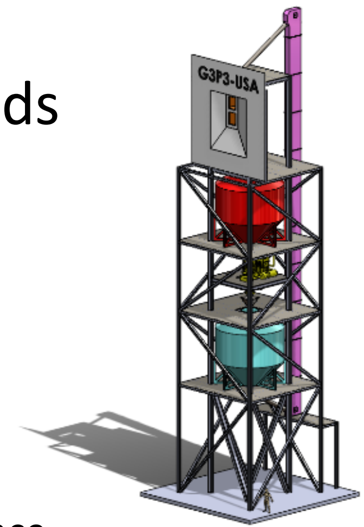
Pacheco et al., JSEE, Development of a Molten-Salt Thermocline Thermal Storage System for Parabolic Trough Plants (2002)

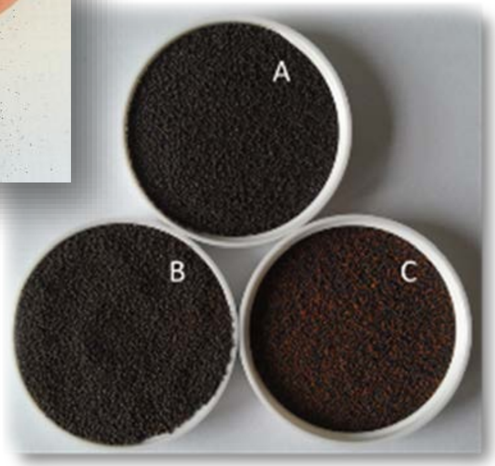
Table 1 Cost of crushed rock, sand, and taconite delivered to Albuquerque, NM

Rock	Cost Material, $/tonne	Transport -ation, $/tonne	Supplier
Limestone, ¾ inch crushed	41	7	Rocky Mountain Stone, Albuquerque, NM
Limestone, 1 inch crushed	15	6	LaFarge, Albuquerque, NM
Limestone, ½ inch crushed	17	6	LaFarge, Albuquerque, NM
Marble, ¾ inch crushed	120	7	Rocky Mountain Stone, Albuquerque, NM
Taconite, 1.2 cm pellets	66	44	Dale Paulson Geneva Steel, Provo, Utah
Quartzite, ¾ inch crushed	43	7	Rocky Mountain Stone, Albuquerque, NM
Silica Sand, 8 mesh	14	3	J.P.R Decorative Gravel, Albuquerque, NM
Filter Sand, 8x12	89	34	Colorado Silica Sand, Colorado Springs, CO
Filter Sand, 6x9	168	34	Colorado Silica Sand, Colorado Springs, CO
Filter Sand, 6x12	153	34	Colorado Silica Sand, Colorado Springs, CO

Particle Materials – Two-Tank CSP

- CARBO Ceramic Beads
  - Cost
    - $1 - $2/kg
  - Durability
    - Low wear/attrition
  - Optical properties
    - High solar absorptance
  - Good flowability
    - Spherical and round
  - Low inhalation hazard





Comparison of Energy Storage Options

Ho, Applied Thermal Engineering, 109 (2016)

	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	Requires large underground caverns	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

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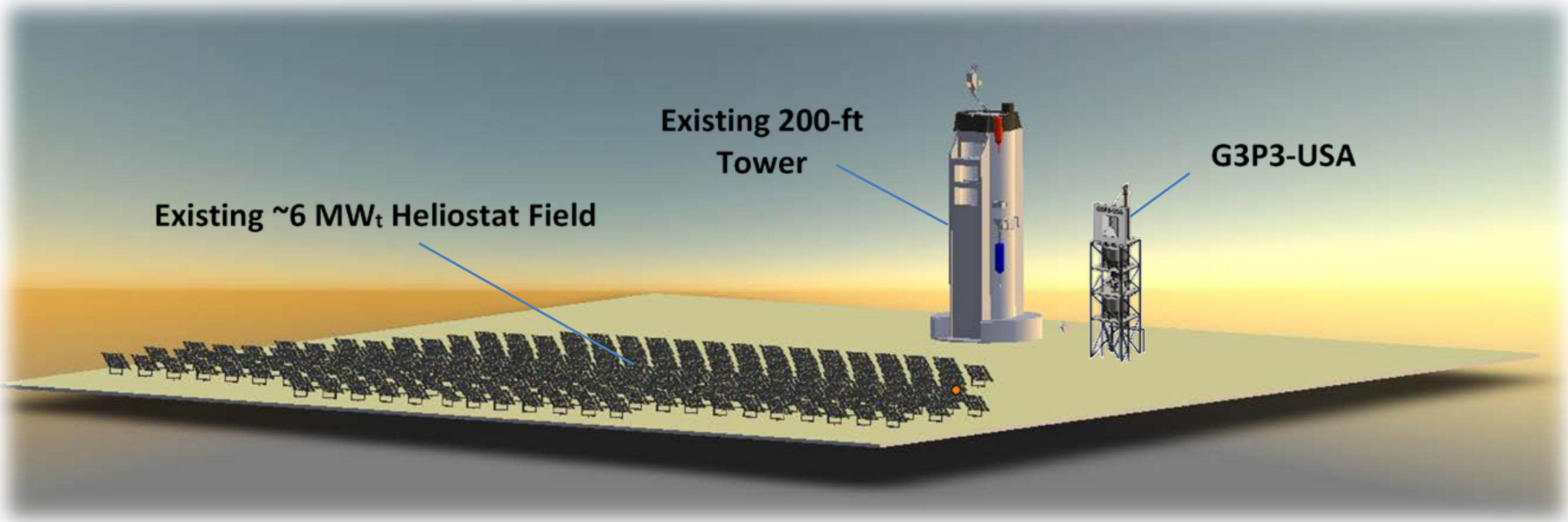
Conclusions

- CSP investigating high-temperature particle storage
  - Ambient to ~1000 °C (no freezing)
  - Single-tank thermocline storage
    - Reduced material, potentially lower cost (30%), thermal ratcheting
  - Two-tank particle storage
    - Requires particle conveyance and heat exchanger
- Particle materials
  - Quartzite rock, silica sand for thermoclines
  - Sintered bauxite (ceramic particles) for CSP G3P3
- Hot particle storage
  - Economical long-duration storage option

Acknowledgments

- This work is funded in part or whole by the U.S. Department of Energy Solar Energy Technologies Office under Award Number 34211

Questions?



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BACKUP SLIDES

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-K)

Sintering Potential of Particles

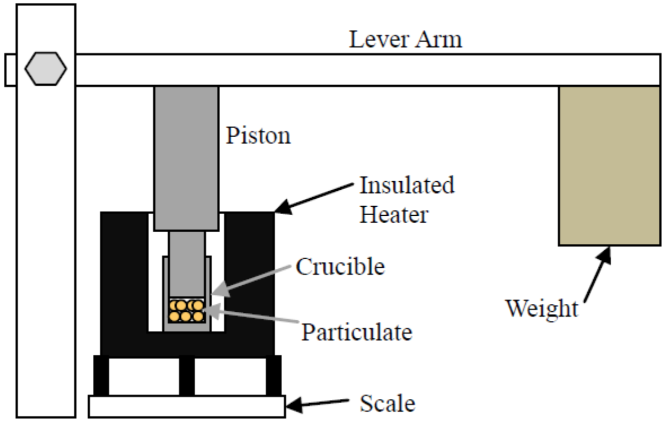


Figure 2. Diagram of Experimental Setup

Figure 3. Image of Experimental Setup

Table 1. Candidate Particulates

Particulate Name	Mineral	Melting Temperature (°C)
Green Diamond (70 x 140)	Olivine	1400 [5]
CARBO*ACCUCAST* ID50-K	Alumina	2000 [6]
Riyadh, Saudi Arabia White Sand	Silica Sand	1600 [7]
Preferred Sands of Arizona Fracking Sand	Silica Sand	1600 [7]
Atlanta Sand & Supply Co. Industrial Sand	Silica Sand	1600 [7]

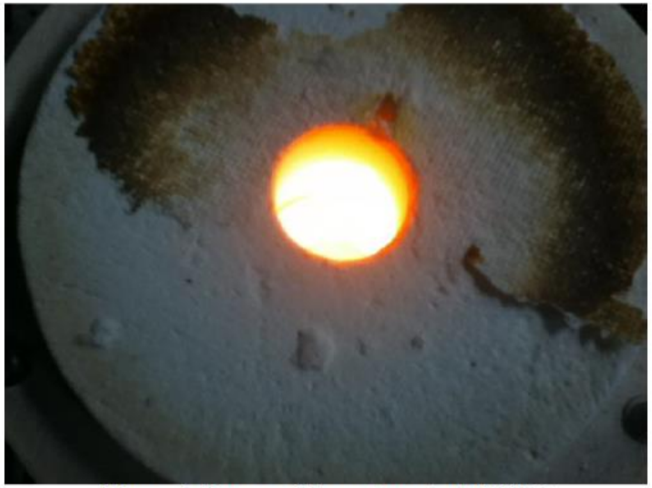
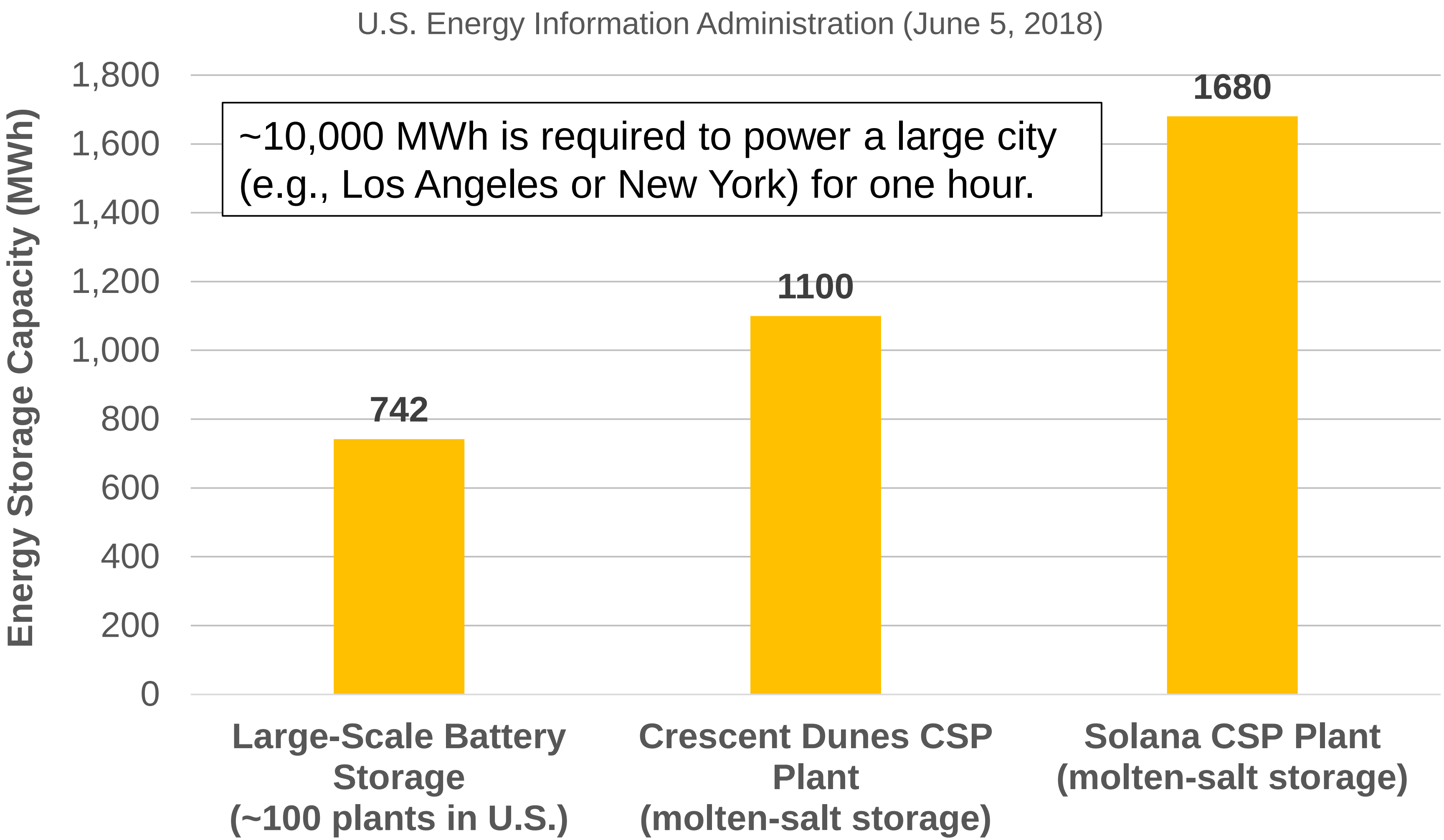


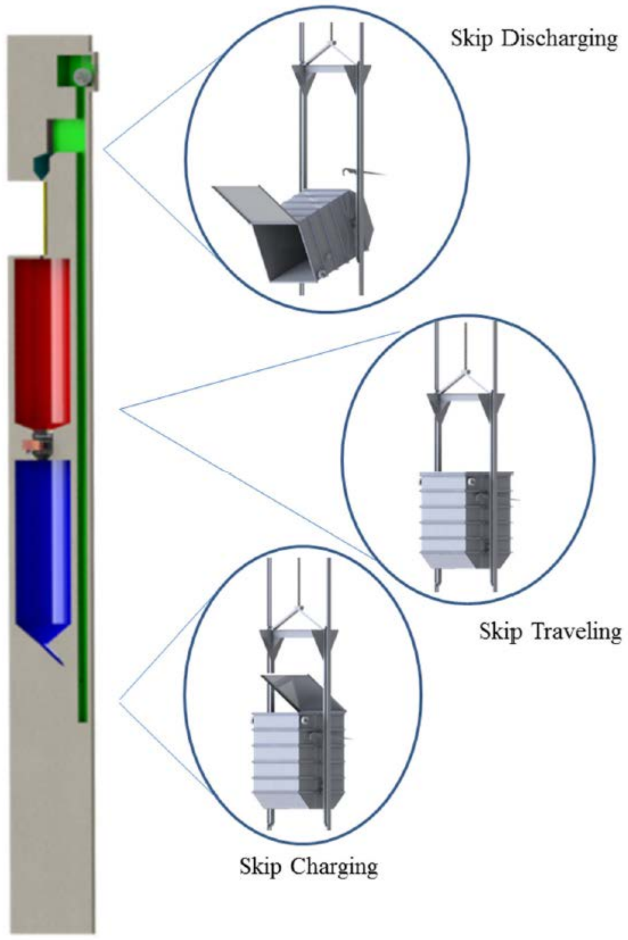
Figure 4. Image of Experiment at 1000°C

Al-Ansary et al., "Characterization and Sintering Potential of Solid Particles for Use in High Temperature Thermal Energy Storage System," SolarPACES 2013

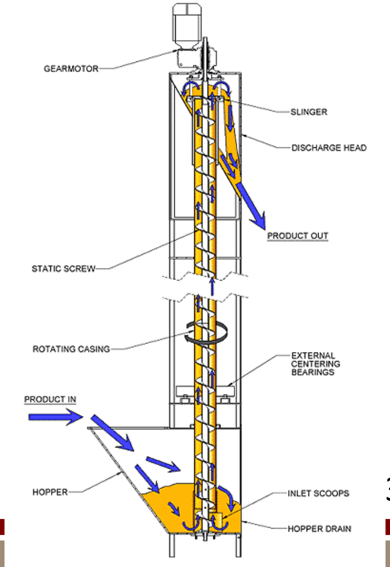
Comparison of Large-Scale Battery and Thermal Energy Storage Capacity in the U.S.



Particle Elevators



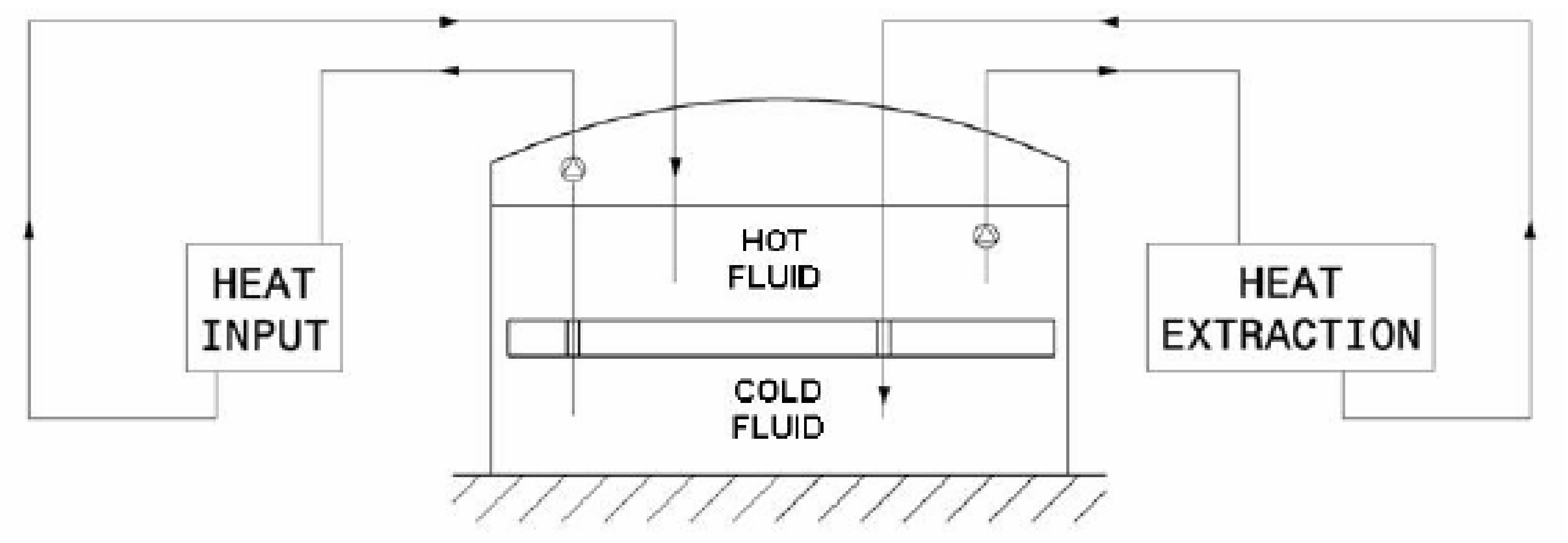
- Evaluate commercial particle lift designs
  - Requirements
    - ~10 – 30 kg/s per meter of particle curtain width
    - High operating temperature ~ 550 °C
  - Different lift strategies evaluated
    - Screw-type (Olds elevator)
    - Bucket
    - Mine hoist



Repole, K.D. and S.M. Jeter, 2016, *Design and Analysis of a High Temperature Particulate Hoist for Proposed Particle Heating Concentrator Solar Power Systems*, in *ASME 2016 10th International Conference on Energy Sustainability, ES2016-59619*, Charlotte, NC, June 26 - 30, 2016.

Alternative Thermocline Design

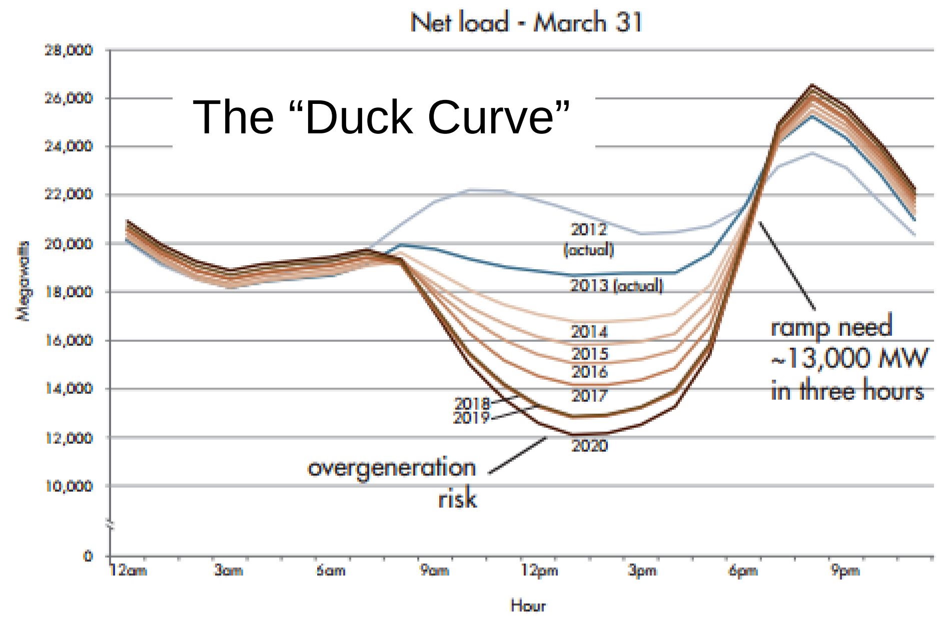
- Single-tank thermocline storage with no filler
  - Uses baffle to separate hot and cold fluids and prevent mixing



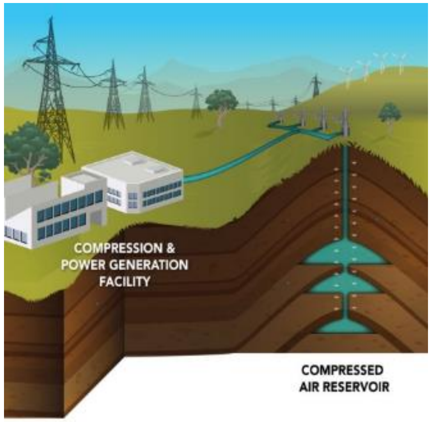
Lata and Blanco, SolarPACES 2010

Problem Statement

- Current renewable energy sources are intermittent
  - Causes curtailment or negative pricing during mid-day
  - Cannot meet peak demand, even at high penetration
- Available energy storage options for solar PV & wind
  - Large-scale battery storage is expensive
    - $\$0.20/kWh_e$ - $\$1.00/kWh_e$
  - Compressed air and pumped hydro – geography and/or resource limited



Source: California Independent System Operator



Need

- Renewable energy technology with reliable, efficient, and inexpensive energy storage

→ Concentrating solar power (CSP) with thermal energy storage