CSP Gen 3 Roadmap

Technology Pathway – Particle Receivers

Gen3 Public Meeting

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Clifford Ho, SNL

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Particle Technology Pathway

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  - Gen 3 Aug. 18-19, 2016 Workshop Participants
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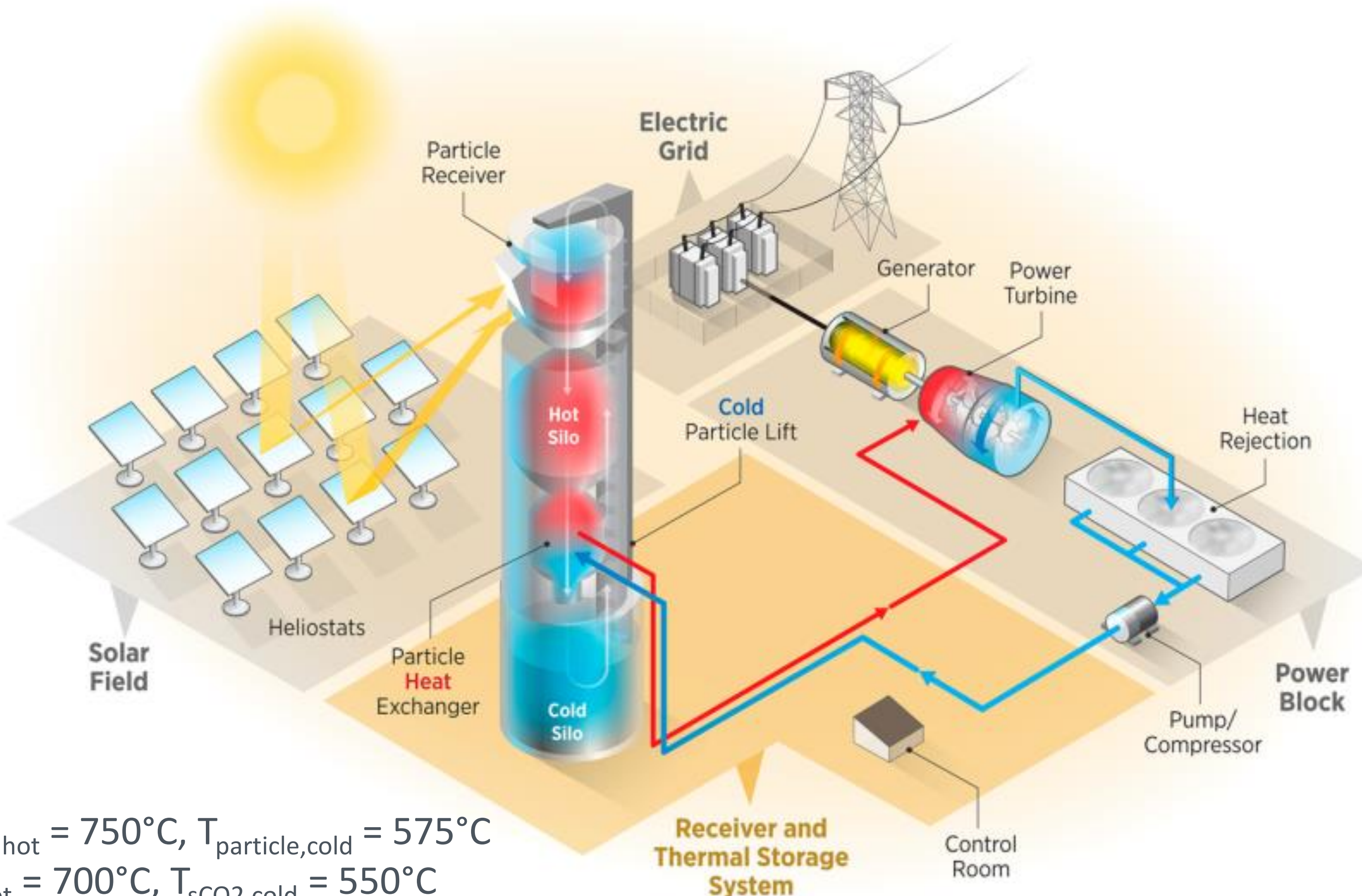
Overview – Particle Technology

- Introduction
- Component Description
- System Integration and Testing
- Summary

Technology Overview – Particle Technology Pathway



$T_{particle,hot}$ = 750°C, $T_{particle,cold}$ = 575°C
$T_{sCO2,hot}$ = 700°C, $T_{sCO2,cold}$ = 550°C
$P_{sCO2,turbine}$ = 20 MPa

Technology Overview - Advantages

- Higher temperatures (>1000 ˚C) than molten salts
  - Enables more efficient power cycles
- Direct heating of particles vs. indirect heating of tubes
  - Higher solar fluxes for increased receiver efficiency
- No freezing or decomposition
  - Avoids costly heat tracing
- Direct storage of hot particles
  - Reduced costs without extra heat exchangers and separate storage media

CARBO ceramic particles (“proppants”)

Technology Overview – History

- Particles as a heat-transfer medium have been studied and commercialized for nearly a century
  - 1920's: First industrialized fluidized particle reactors for coal gasification
  - 1940's: First circulating fluidized bed for catalytic cracking of mineral oils and metallurgical processing
  - 1960's: First fluidized bed for combustion of coal in a power plant in Germany
  - 1980's: Particle receivers first evaluated for CSP
  - 2007: First on-sun falling-particle receiver test
  - 2015: First high-temperature (>700 C) continuously recirculating on-sun particle receiver tests
  - 2016: First fluidized-bed CSP plant in Sicily

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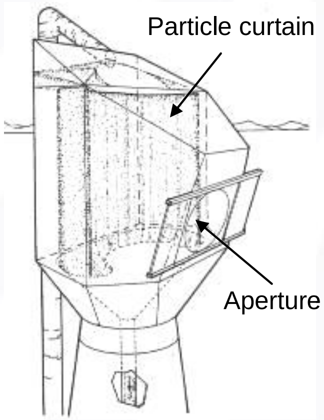
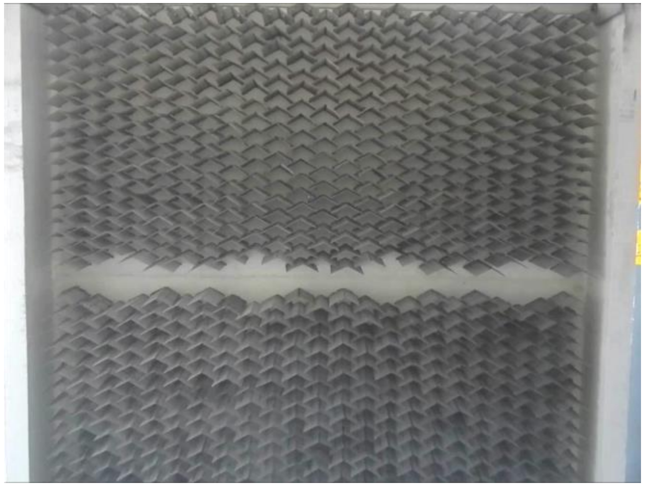
Receiver

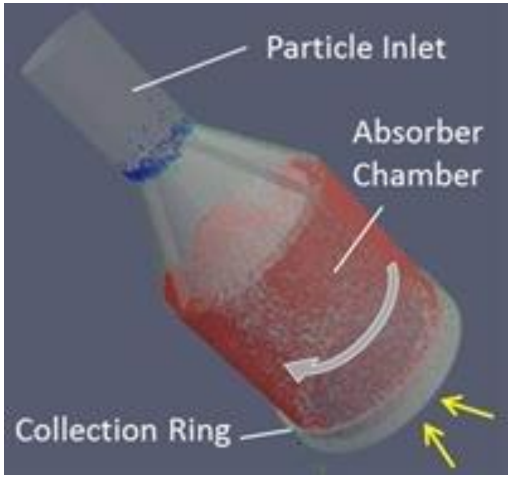


Alternative Receiver Designs

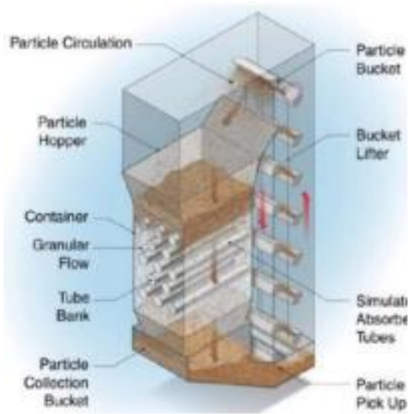
Free-Falling (SNL)



Obstructed Flow (GT)



Centrifugal (DLR)



Enclosed Flow (NREL)

Solid Graphite (Graphite Energy)

PROMES CNRS

Fluidized Bed/Tubes

Particles

Properties of Alternative Particles

Material	Image	Composition	Properties		Advantage	Dis-advantage
			Density (kg/m^3)	Specific Heat (J/kg-K)		
Silica sand		SiO_2	2,610	1,000	Stable, abundant, low cost	Low solar absorptivity and conductivity
Alumina		Al_2O_3	3,960	1,200	Stable	Low absorptivity
Coal ash		SiO_2, Al_2O_3, + minerals	2,100	720 at ambient temp	Stable, abundant, No/low cost	Identify suitable ash
Calcined Flint Clay		SiO_2, Al_2O_3, TiO_2,Fe_2O_3	2,600	1,050	Mined abundant	Low absorptivity
Ceramic proppants		75% Al_2O_3, 11%SiO_2, 9%Fe_2O_3, 3%TiO_2	3,300	1,200 (at 700°C)	High solar absorptivity, stable	Synthesized, higher cost

Particle Durability

- Laboratory tests for surface impact evaluation, attrition, and sintering

Ambient drop tests at ~10 m

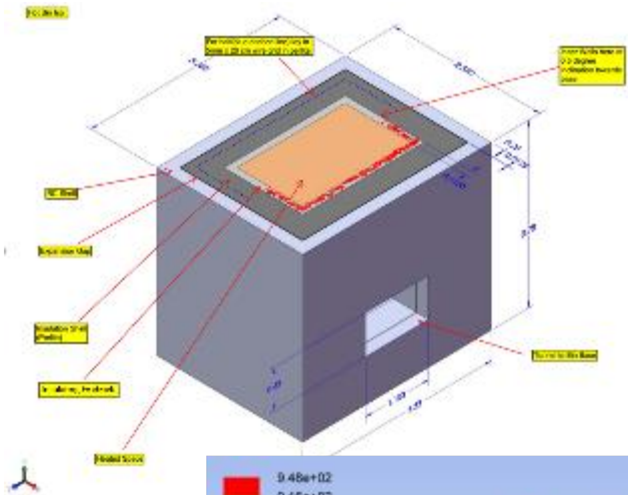
Thousands of drop cycles at ambient and elevated temperatures (up to 1000 °C)

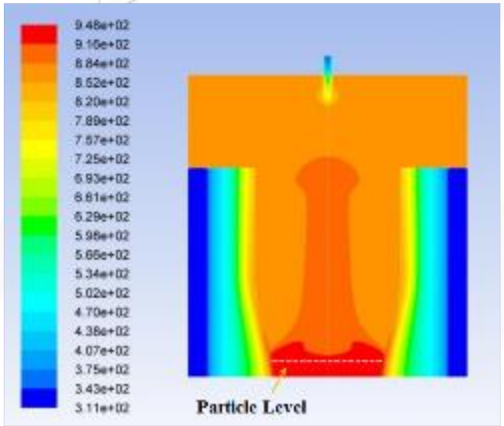
Knott, R., D.L. Sadowski, S.M. Jeter, S.I. Abdel-Khalik, H.A. Al-Ansary, and A. El-Leathy, 2014, *High Temperature Durability of Solid Particles for Use in Particle Heating Concentrator Solar Power Systems*, in *Proceedings of the ASME 2014 8th International Conference on Energy Sustainability*, ES-FuelCell2014-6586, Boston, MA, June 29 - July 2, 2014.

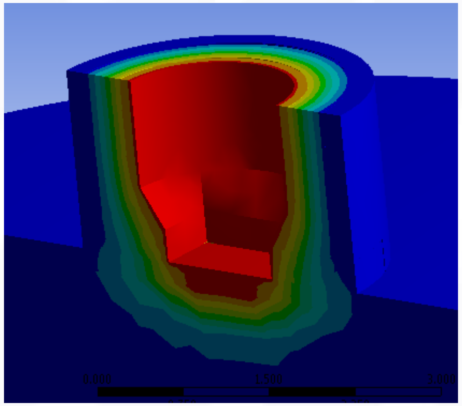
Balance of Plant

Thermal Storage

- Experimental evaluation and modeling of prototype thermal energy storage designs



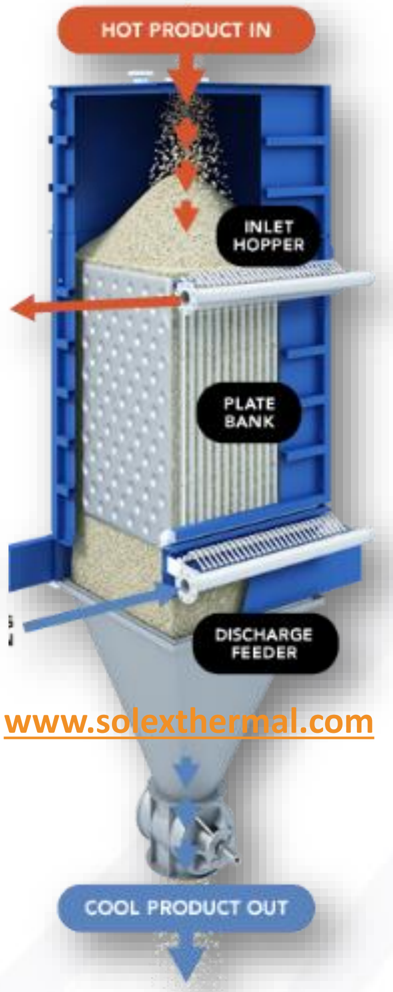




El-Leathy et al., "Experimental Study of Heat Loss from a Thermal Energy Storage System for Use with a High-Temperature Falling Particle Receiver System," SolarPACES 2013

Particle to Working Fluid Heat Exchanger

- Evaluation of heat transfer coefficients & particle flow



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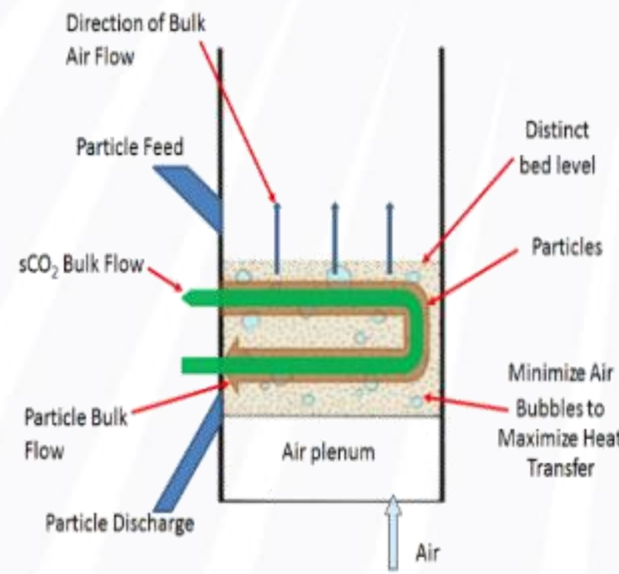
SOLEX THERMAL SCIENCE

VPE VACUUM PROCESS ENGINEERING

Moving Packed-Bed Shell-and-Tube and Shell-and-Plate Heat Exchanger

B&W thebabcock&wilcoxcompany

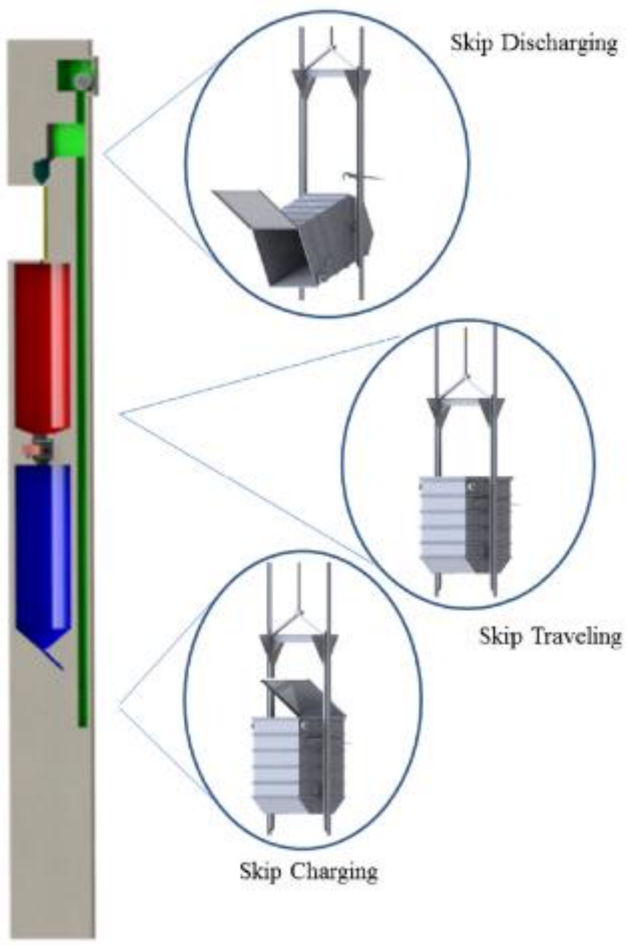
Fluidized-Bed Heat Exchanger



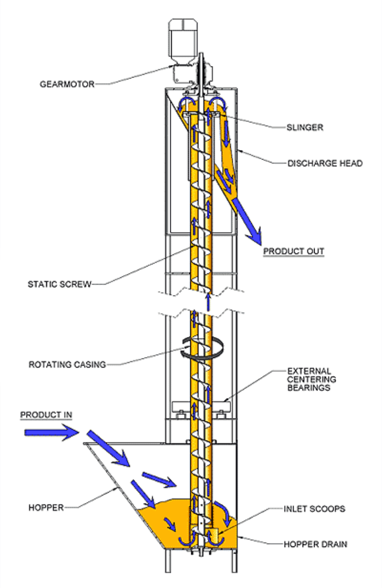
Golob et al., 2013, "Serpentine Particle-Flow Heat Exchanger with Working Fluid, for Solar Thermal Power Generation," SolarPACES 2013

Nguyen, C., D. Sadowski, A. Alrished, H. Al-Ansary, S. Jeter, and S. Abdel-Khalik, 2014, Study on solid particles as a thermal medium, *Proceedings of the Solarpaces 2013 International Conference*, **49**, p. 637-646.

Particle Elevators



- Evaluate commercial particle lift designs
  - Requirements
    - ~10 – 50 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.

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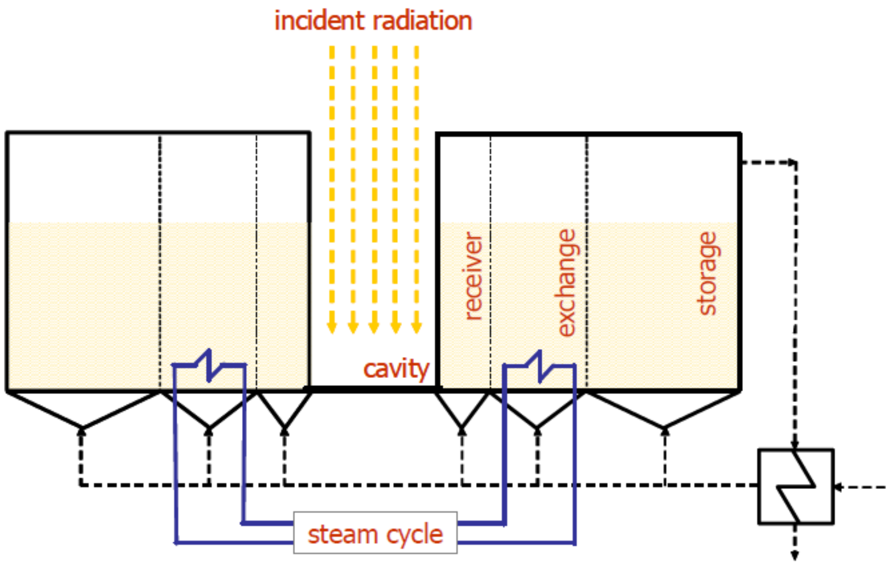
300 kW_t Particle Receiver System - King Saud University

Professor Hany Al-Ansary

- 300 kW_t heliostat field
- Obstructed flow particle receiver
- Particle storage system
- Particle heat exchanger
- Olds elevator particle lift
- Air Brayton power cycle

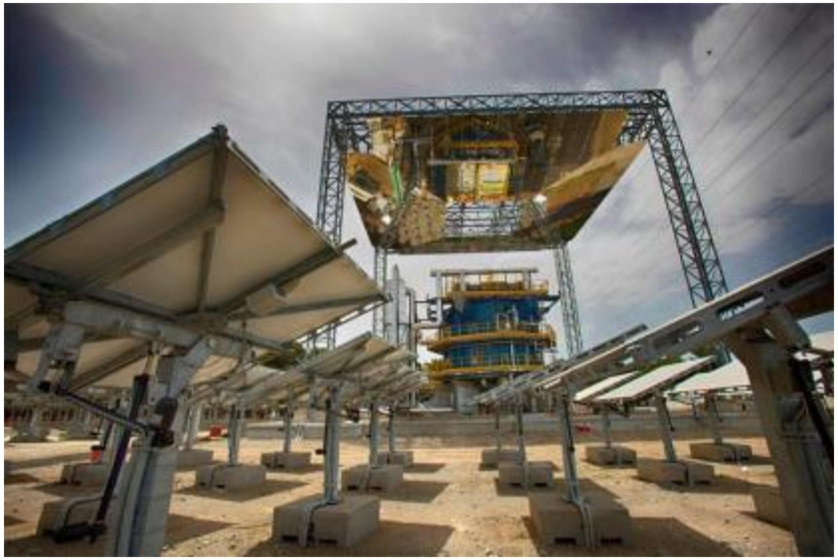
2 MW$_t$ Fluidized-Bed Power Plant – Sicily, Italy

Magaldi Group



Chirone et al. 2013

- 2 MW$_t$ modular beam-down fluidized-bed receiver units
- Superheated steam at 520 C
- 6 hours thermal storage

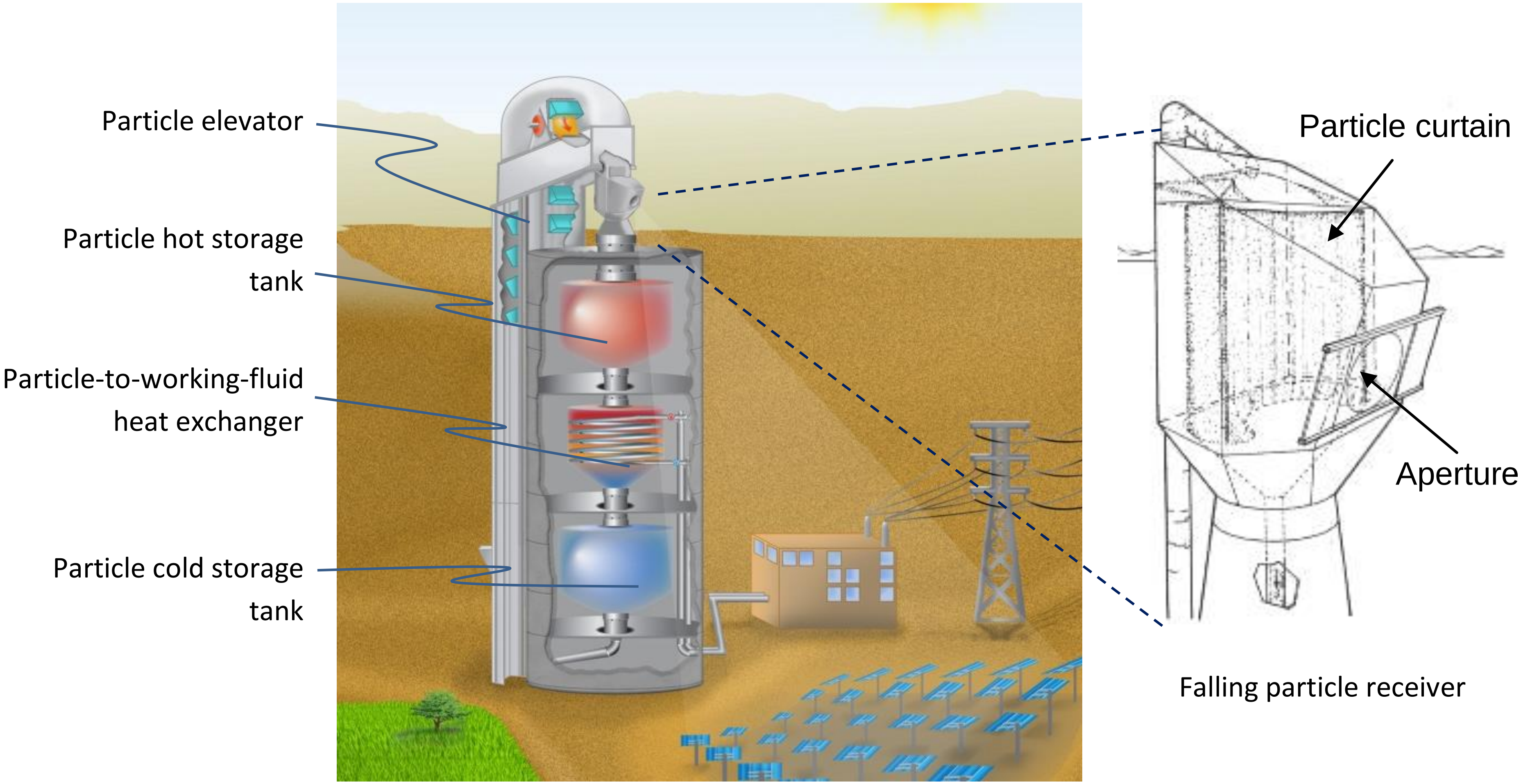


Source: http://blog.bulk-online.com/news-english/magaldi-the-first-stem-solar-thermo-electric-magaldi-plant-starts-operations-in-sicily.html

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

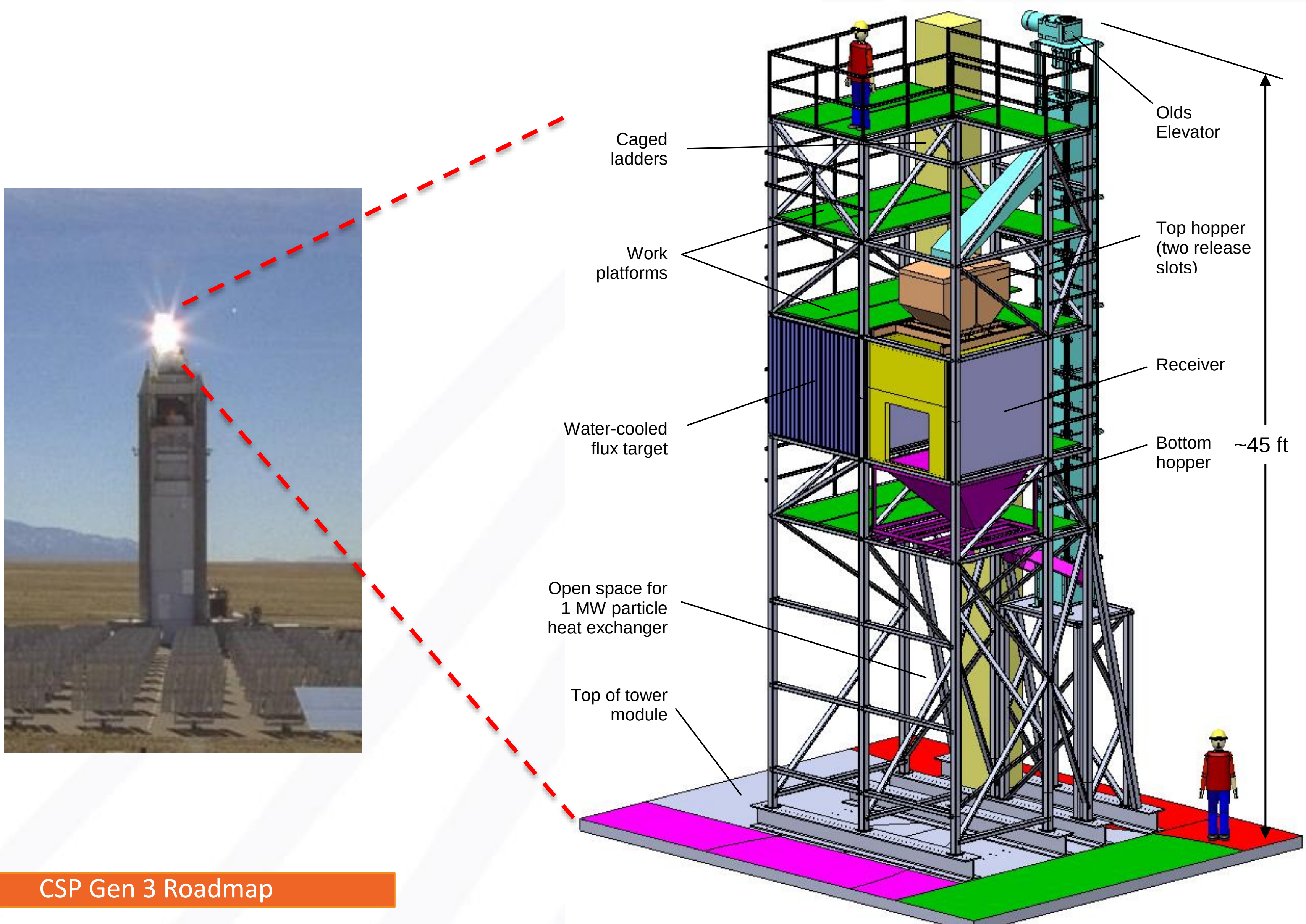
- Graphite block is heated in face-down receiver
- Used to heat steam from 200 °C to 500 °C
  - Powers a 3 MW_e steam-Rankine cycle.

High Temperature Falling Particle Receiver
(DOE SunShot Award FY13 – FY16)

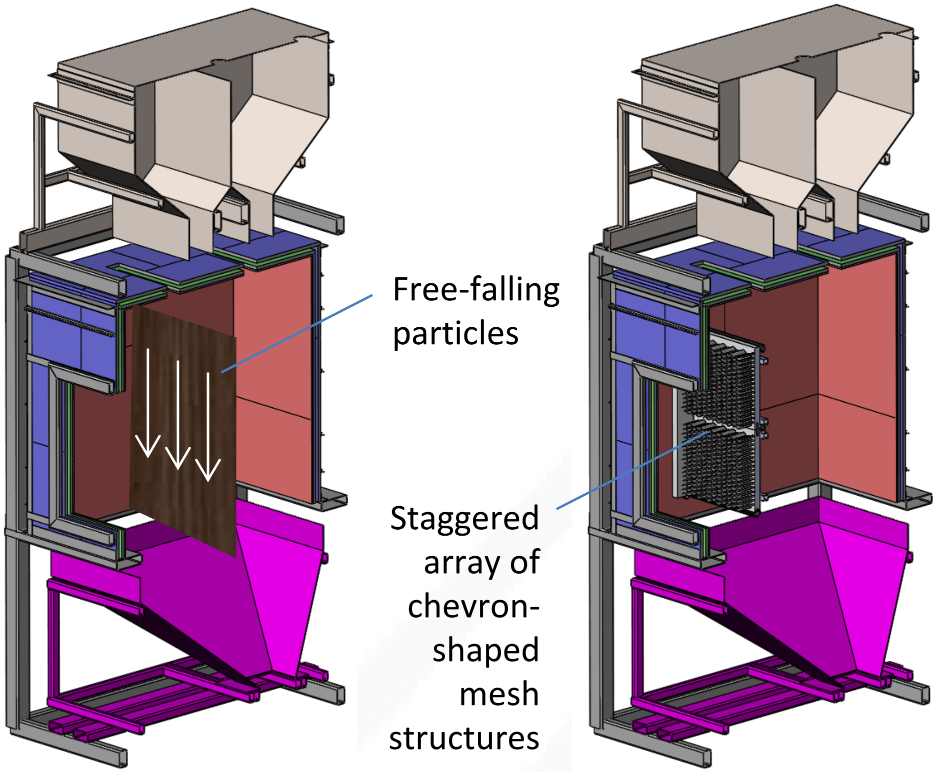


Goal: Achieve higher temperatures, higher efficiencies, and lower costs

Sandia 1 MW_t Falling Particle Receiver



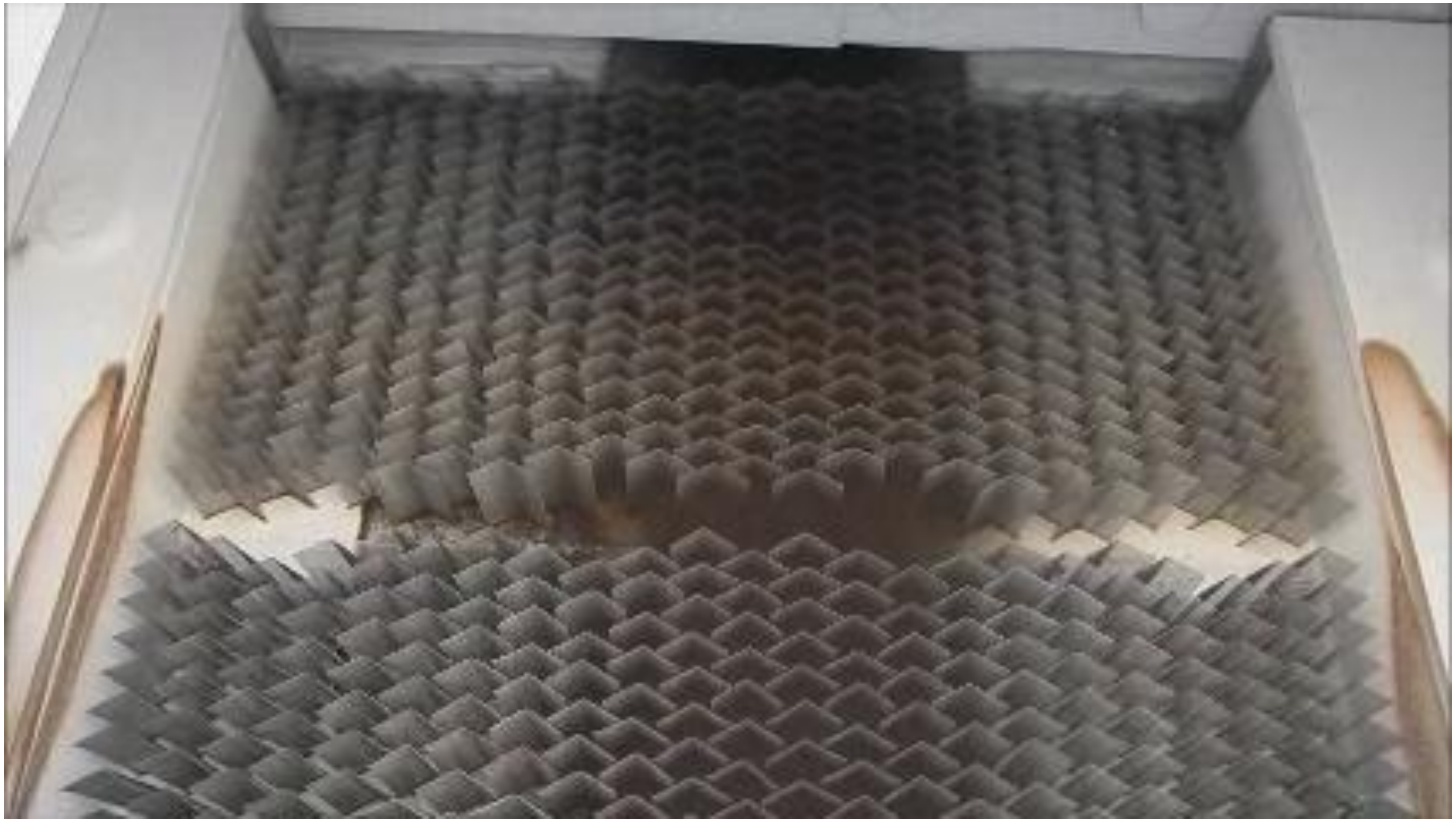
Particle Release Configurations



On-Sun Tower Testing

Over 600 suns peak flux on receiver
(July 20, 2015)

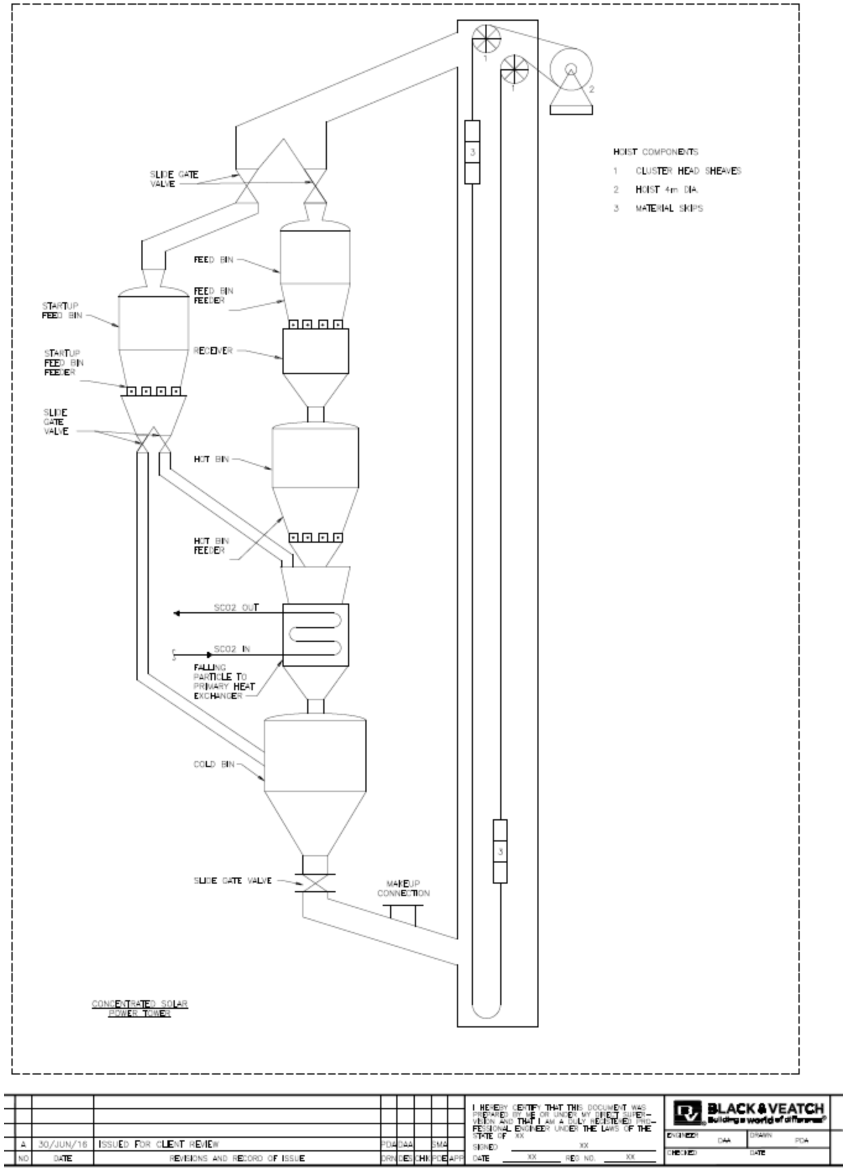
On-Sun Tower Testing



Particle Flow Through Mesh Structures
(June 25, 2015)

Black & Veatch System Analysis

- Black and Veatch, "Falling Particles Concept Definition & Capital Cost Estimate," 2016



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Summary – Solid-based/particle receivers

- Advantages
  - Wide temperature range
    - No freezing; can achieve > 1000 °C
    - No trace heating
  - Direct heating of particles (high concentration ratios)
  - Direct storage of inexpensive particles
  - Particle handling/heat exchange/storage well established
- Challenges
  - Particle durability, attrition (dust emission)
  - Receiver efficiency
    - Reduce convective/radiative losses
    - Increase particle/wall heat transfer
  - Particle-to-sCO_2 heat exchanger at 700 °C, 20 MPa
  - Demonstration at larger scales (~10 – 100 MW_{th})

International Energy Agency / SolarPACES Particle Technology Working Group

- Objective
  - Initiate coordination among particle researchers to create a shared database of particle research, needs/gaps, collaborative opportunities
- Power/Heating/Storage
  - Australia, China, France, Germany, Italy, Saudi Arabia, Spain, UAE, USA
- Thermochemistry/Solar Fuels
  - Australia, Germany, Japan, Spain, Switzerland, USA

International Energy Agency

Questions?

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