



Gen3 CSP Workshop

High-Temperature Particle Technology Pathway

Contributors:

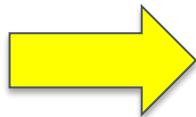
Sandia National Laboratories
Georgia Institute of Technology
Bucknell University
King Saud University
German Aerospace Center (DLR)

Overview

- Introduction
- Particle Receiver System
- On-Sun Testing
- Findings, Gaps, and Needs

Motivation

- Higher Efficiency Electricity Production
 - Supercritical CO₂ Brayton Cycles (>700 °C)
 - Air Brayton Combined Cycles (>1000 °C)
- Thermochemical Storage & Fuels
 - ELEMENTS redox particles (>1000 °C)
 - Solar fuel production (>1000 °C)



Particle Receivers

Advantages of Particle Receivers

- Direct heating of particles
 - Higher temperatures than conventional molten salts
 - Enable more efficient power cycles
 - Higher solar fluxes for increased receiver efficiency
- Direct storage of hot particles
 - Reduced costs



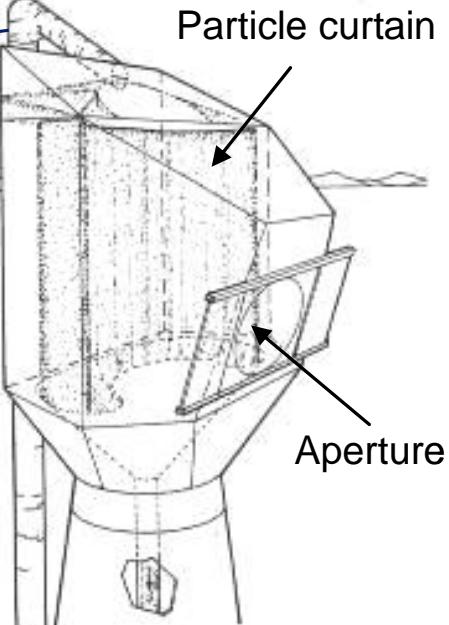
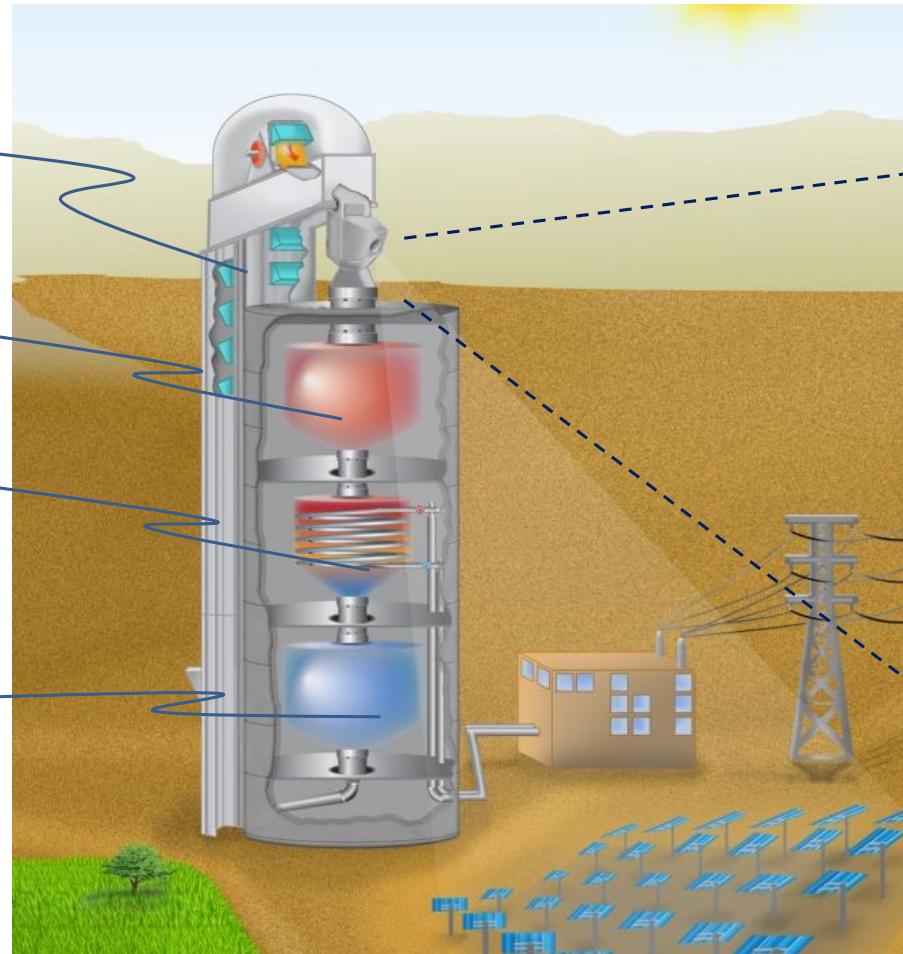
CARBO ceramic particles (“proppants”)



High Temperature Falling Particle Receiver

(DOE SunShot Award FY13 – FY16)

Particle elevator
Particle hot storage tank
Particle-to-working-fluid heat exchanger
Particle cold storage tank



Falling particle receiver



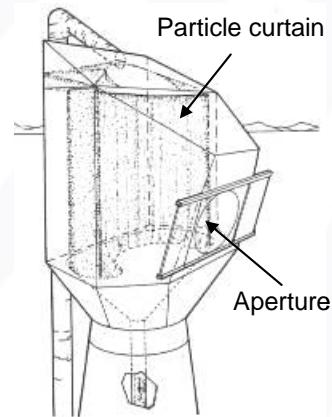
Goal: Achieve higher temperatures, higher efficiencies, and lower costs

Overview

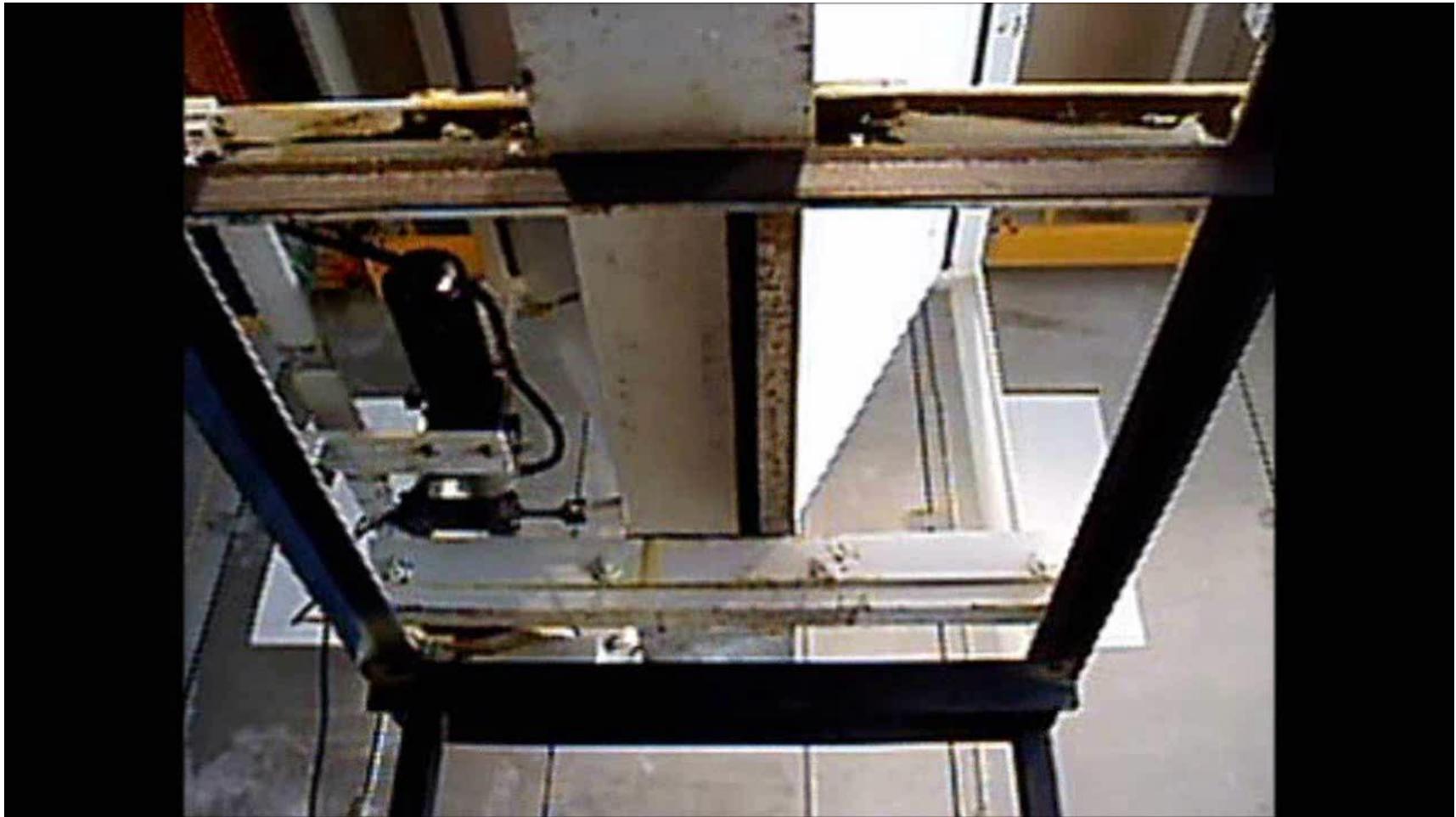
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Receiver

Free-Fall vs. Obstructed Flow



Particle Receiver Designs – Free Falling



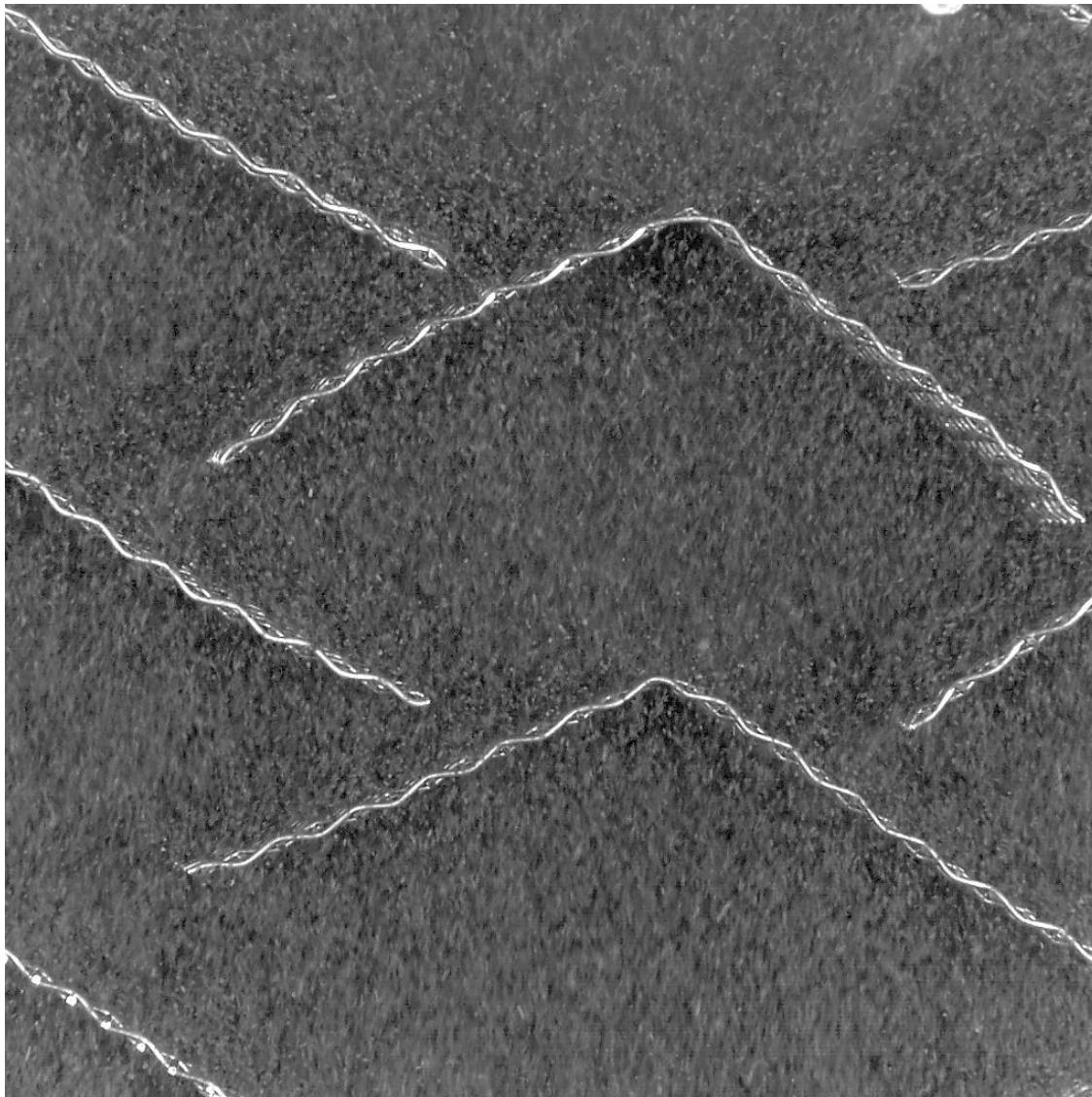
Particle Receiver Designs – Free Falling



Particle Receiver Designs – Pachinko



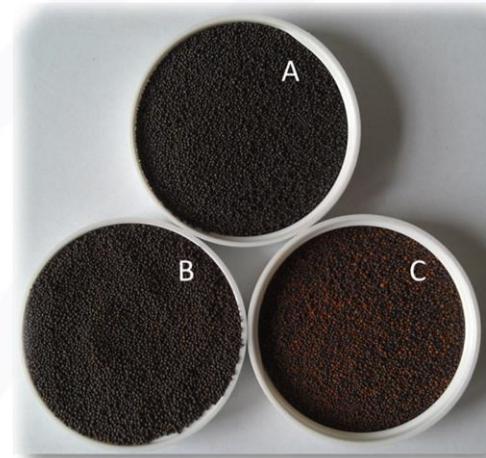
Particle Flow over Chevron Meshes



Pros: particle velocity reduced for increased residence time and heating

Cons: Mesh structures exposed to concentrated sunlight (~1000 suns)

Particles



Particle Radiative Properties

Material Name	Type	Solar weighted absorptivity	Thermal emissivity*	Selective Absorber Efficiency**
Carbo HSP	Sintered Bauxite	0.934	0.843	0.864
CarboProp 40/70	Sintered Bauxite	0.929	0.803	0.862
CarboProp 30/60	Sintered Bauxite	0.894	0.752	0.831
Accucast ID50K	Sintered Bauxite	0.906	0.754	0.843
Accucast ID70K	Sintered Bauxite	0.909	0.789	0.843
Fracking Sand	Silica	0.55	0.715	0.490
Pyromark 2500	Commercial Paint	0.97	0.88	0.897

*Spectral directional reflectance values were measured at room temperature. The total hemispherical emissivity was calculated assuming a surface temperature of 700 °C.

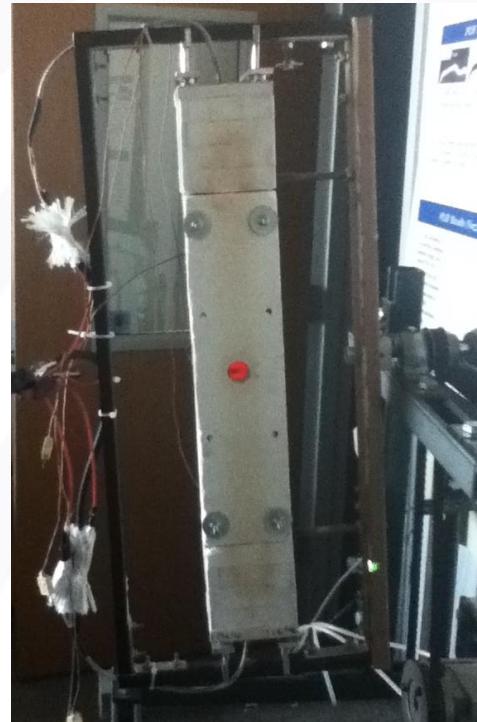
**Q is assumed to be $6 \times 10^5 \text{ W/m}^2$ and T is assumed to be 700 °C (973 K): $\eta_{sel} = \frac{\alpha_s Q - \varepsilon \sigma T^4}{Q}$

Particle Durability

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



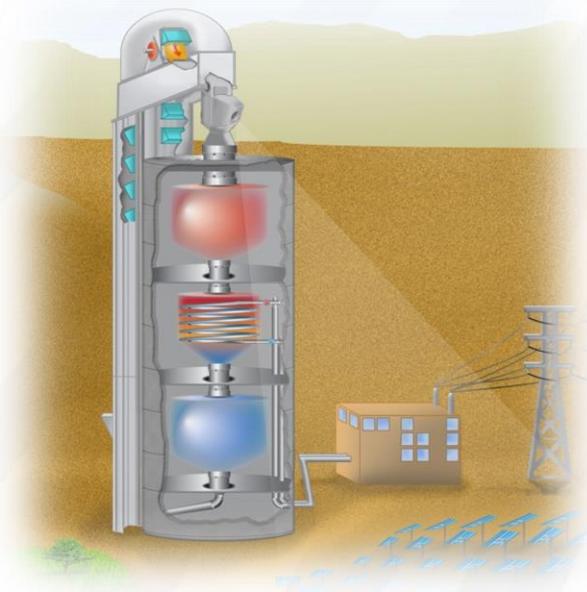
Ambient drop tests at ~ 10 m



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

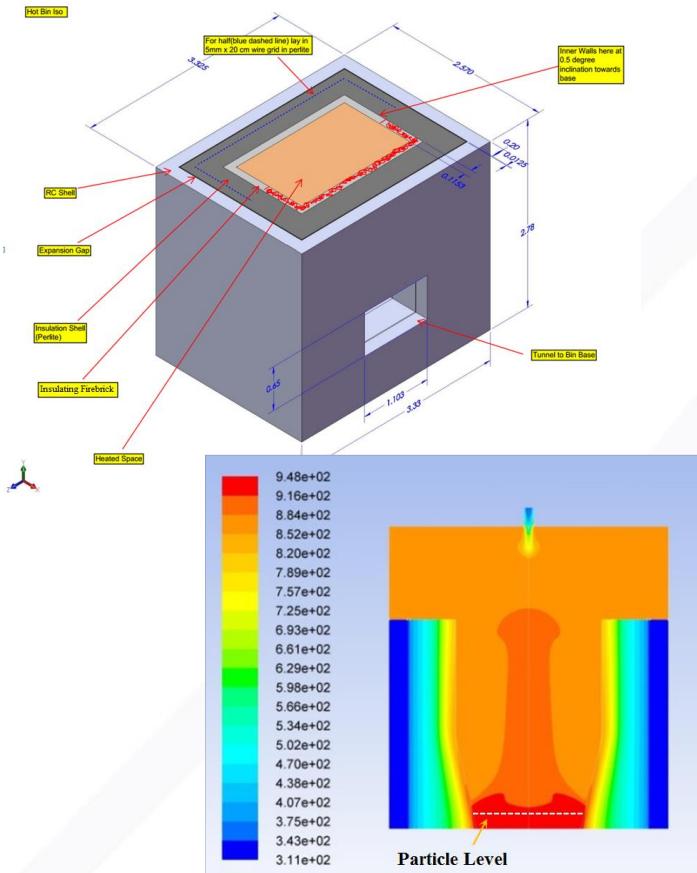
Knott, R., D.L. Sadowski, S.M. Jeter, S.I. Abdel-Khalik, H.A. Al-Ansary, and A. El-Leathy, 2014, *High Temperature Durability of Solid Particles for Use in Particle Heating Concentrator Solar Power Systems*, in *Proceedings of the ASME 2014 8th International Conference on Energy Sustainability*, ES-FuelCell2014-6586,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

Balance of Plant



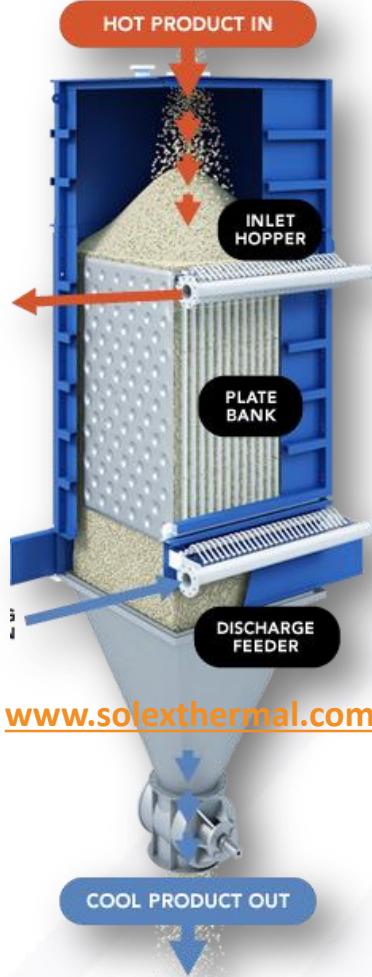
Thermal Storage

- Experimental evaluation and modeling of prototype thermal energy storage designs



Particle to Working Fluid Heat Exchanger

- Evaluation of heat transfer coefficients & particle flow



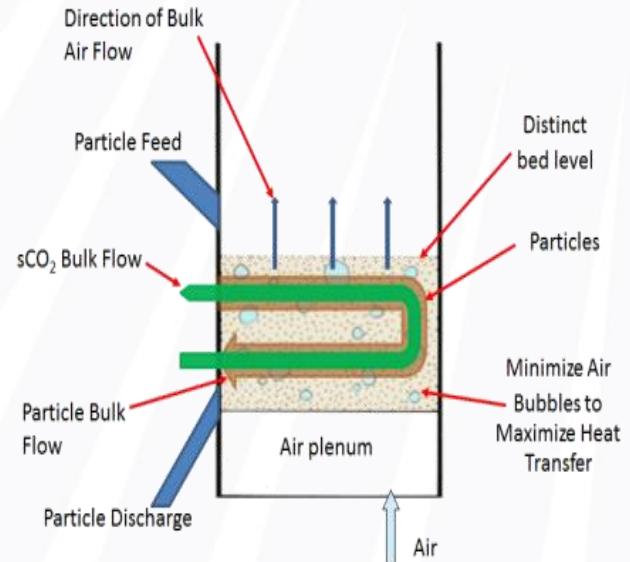
VACUUM PROCESS ENGINEERING

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

www.solexthermal.com



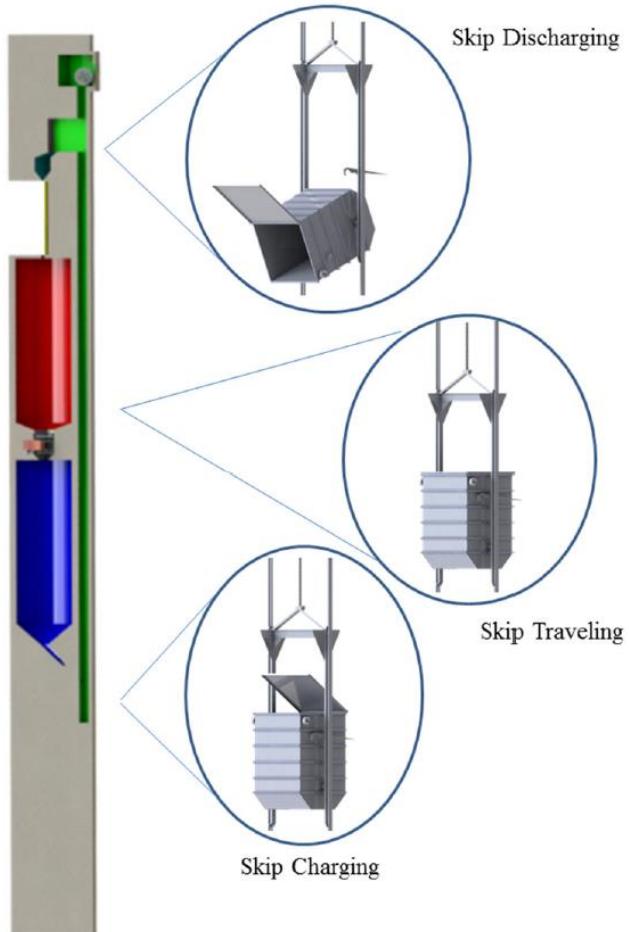
Fluidized-Bed Heat
Exchanger



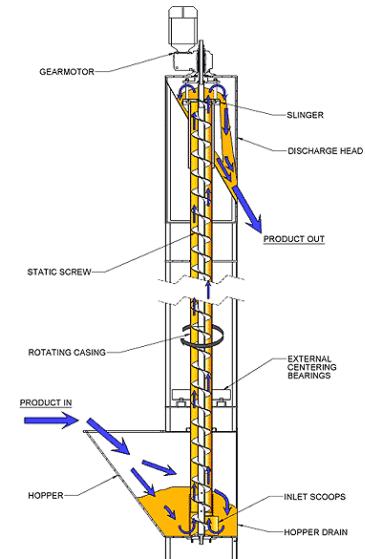
Golob et al., 2013, "Serpentine Particle-Flow Heat Exchanger with Working Fluid, for Solar Thermal Power Generation," SolarPACES 2013

Nguyen, C., D. Sadowski, A. Alrashed, 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
 - $\sim 10 - 30$ kg/s per meter of particle curtain width
 - High operating temperature ~ 550 °C
 - Different lift strategies evaluated
 - Screw-type (Olds elevator)
 - Bucket
 - Mine hoist

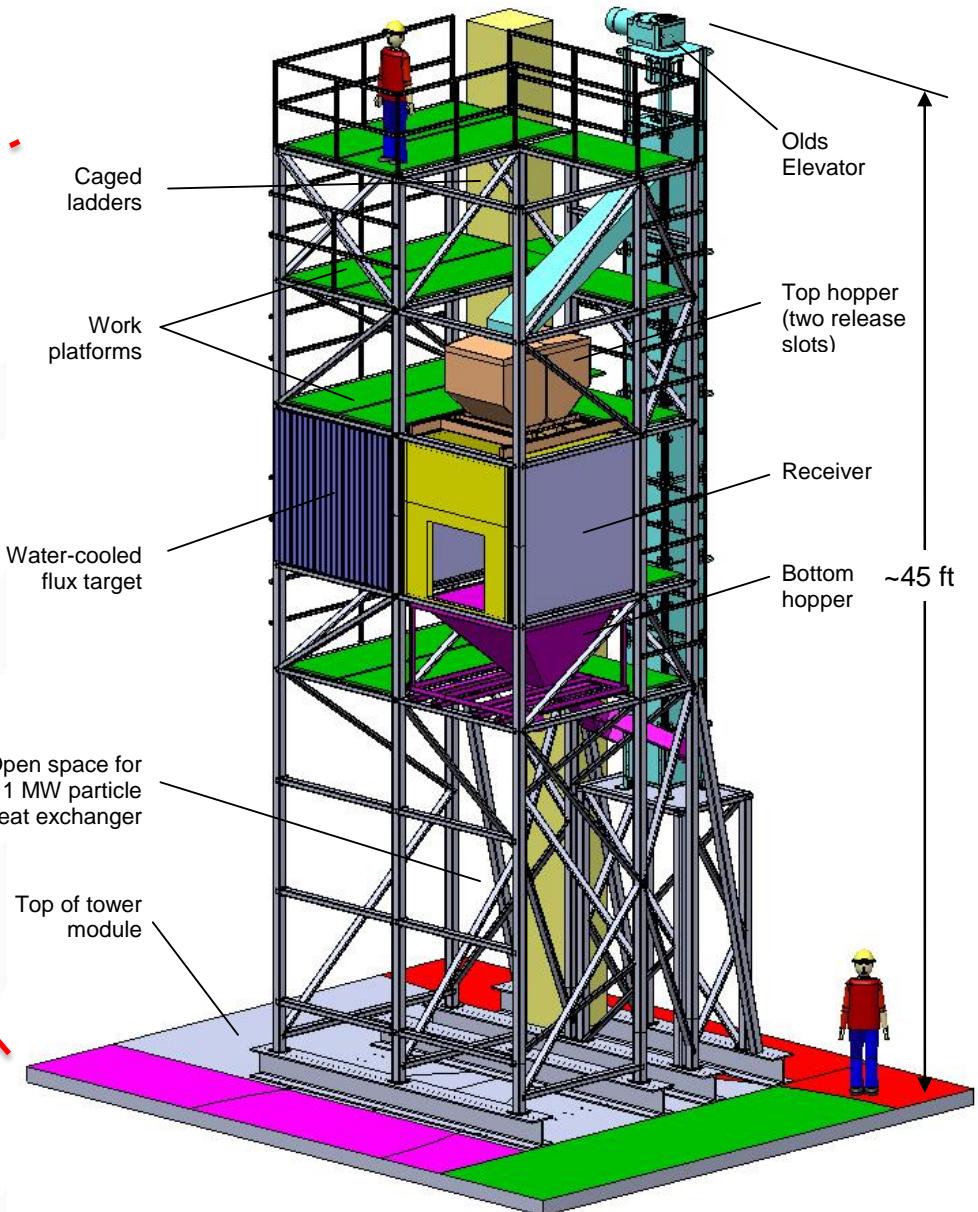
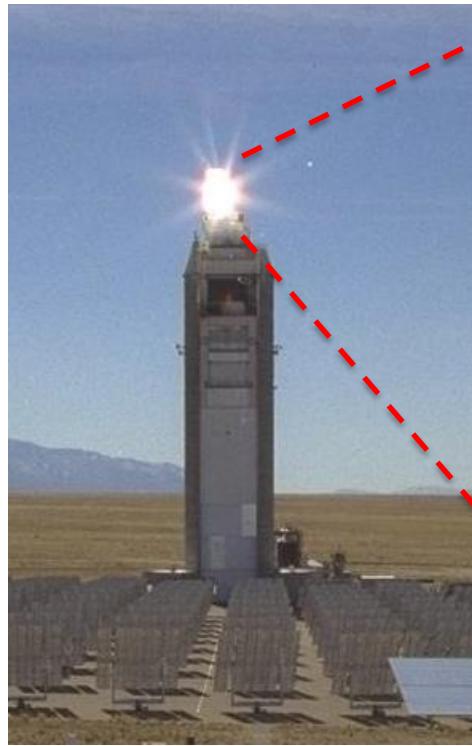


Repole, K.D. and S.M. Jeter, 2016, *Design and Analysis of a High Temperature Particulate Hoist for Proposed Particle Heating Concentrator Solar Power Systems*, in ASME 2016 10th International Conference on Energy Sustainability, ES2016-59619, Charlotte, NC, June 26 - 30, 2016.

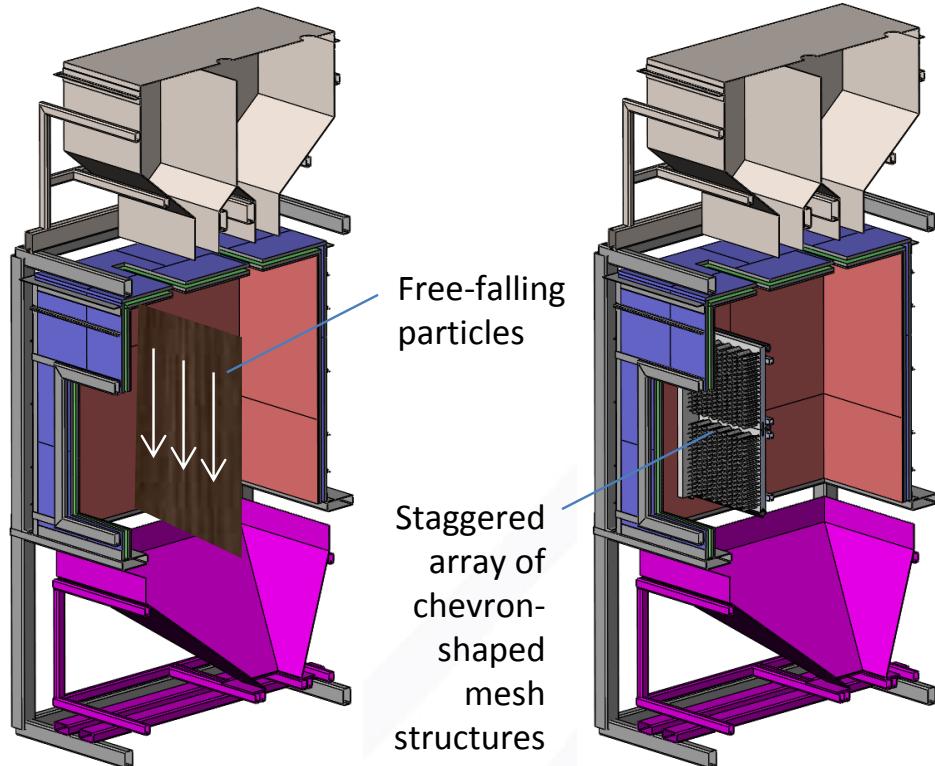
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Prototype System Design



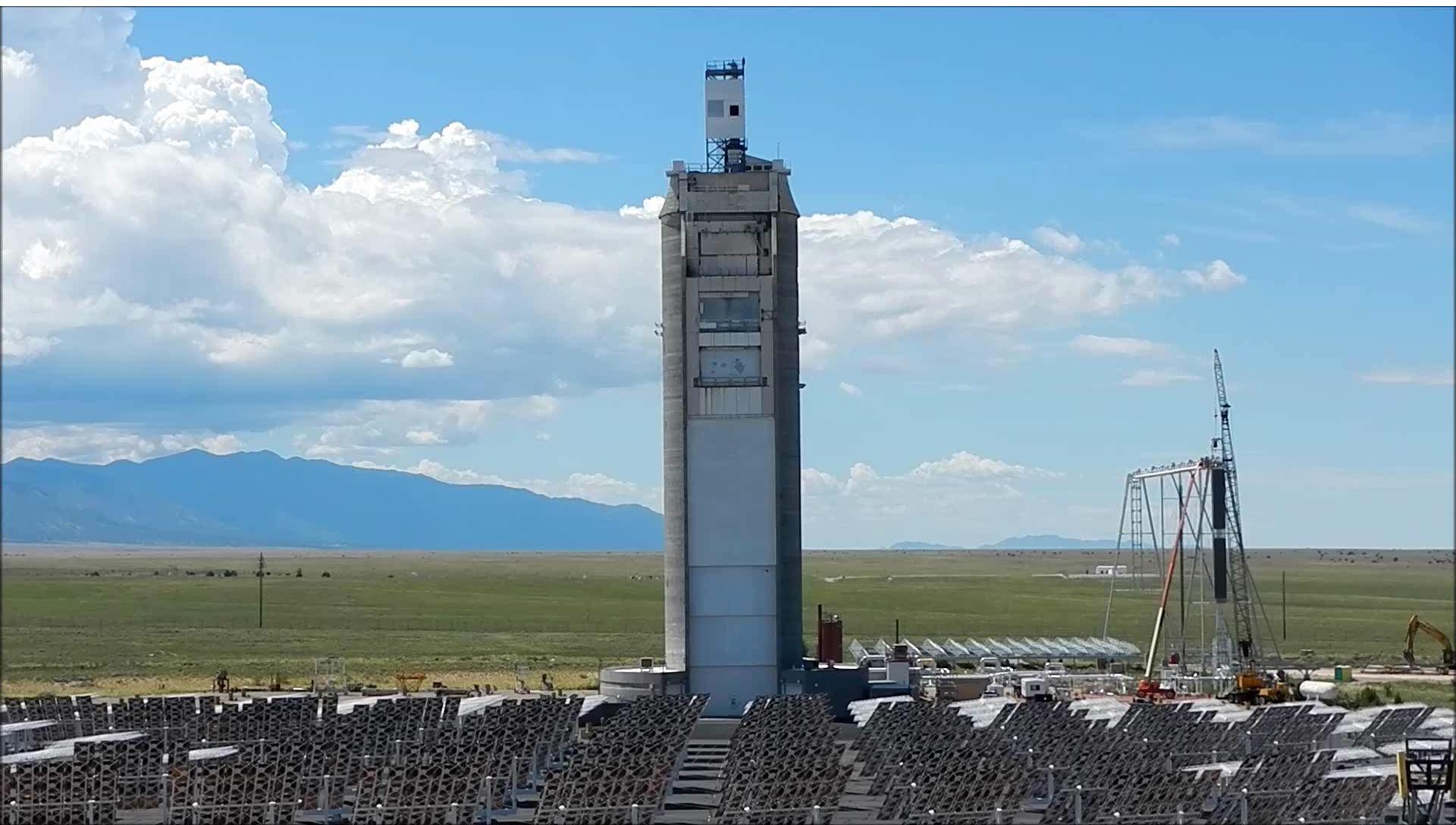
Particle Release Configurations



Lifting the system to the top of the tower



On-Sun Tower Testing



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

On-Sun Tower Testing



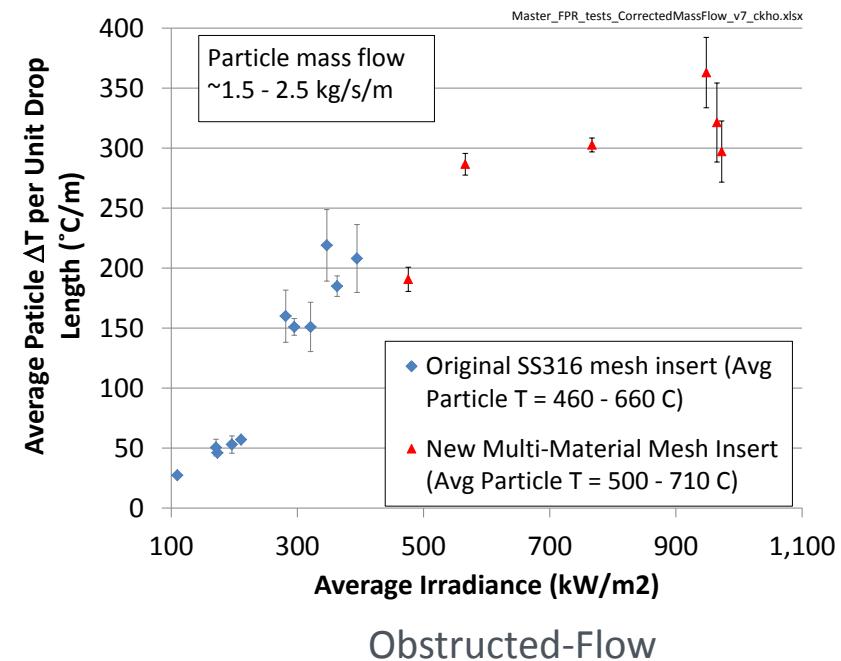
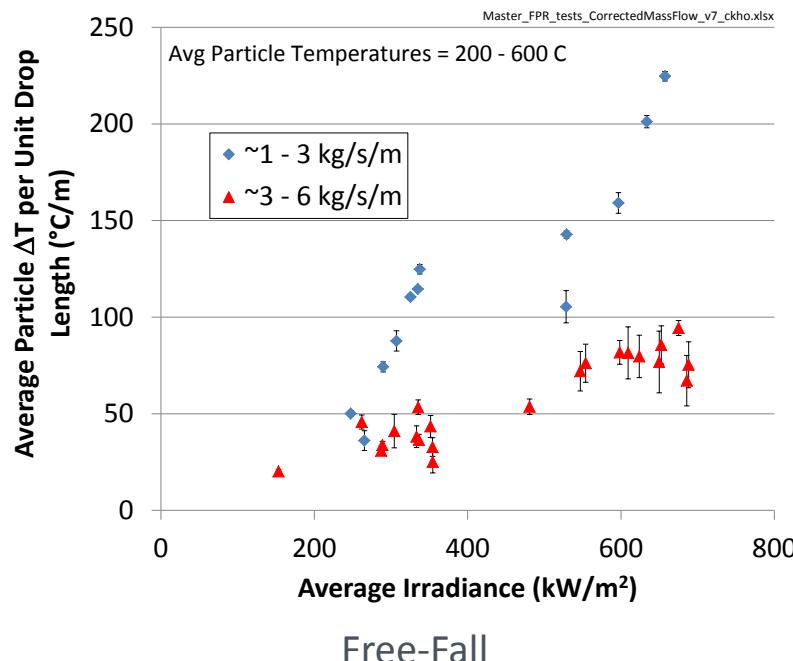
Particle Flow Through Mesh Structures
(June 25, 2015)

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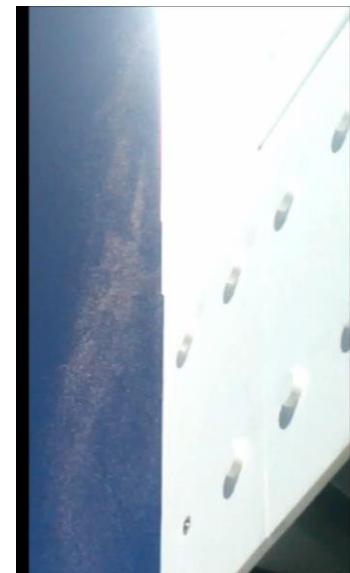
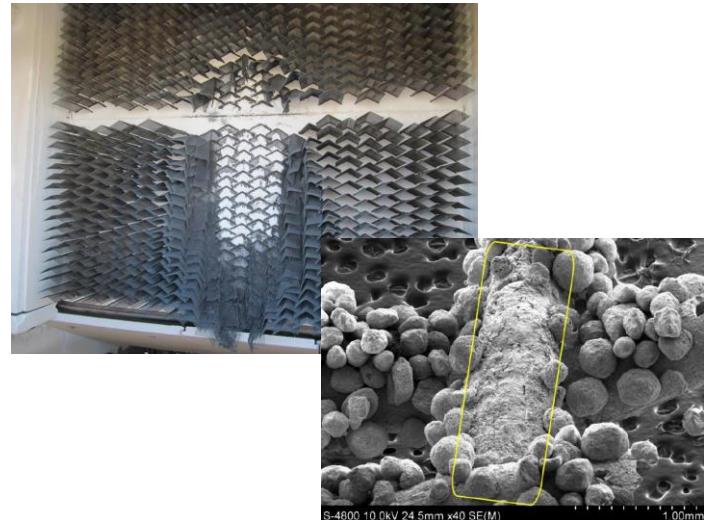
Findings

- Achieved average particle outlet temperatures up to 800 °C
 - Peak particle outlet temperatures > 900 °C
- Particle heating up to $\sim 200 - 300$ °C/(m of drop); 1 – 3 kg/s
- Thermal efficiency up to $\sim 70\%$ to 80%



Lessons Learned

- Mesh materials (SS316) showed signs of wear
 - Evaluate alternative alloys or ceramics
- Particle mass flow was reduced at higher temperatures
 - Two reasons:
 - Narrowing of discharge slot
 - Higher particle/wall friction coefficient
 - Need active particle mass flow control and monitoring
- Particle loss was 0.06% of mass flow rate
 - 60% from loss through aperture (5.8 kg/hr)
 - 40% from attrition due to abrasion (3.6 kg/hr)
 - Mitigations
 - Deeper cavity; particle release further from aperture
 - Use low-particle-friction elevators



Particle loss from aperture during on-sun test

Gaps and Needs



- Particle Receiver
 - Improve thermal efficiency from 70 – 80% to 90%
 - Receiver geometry, shape, size, nod angle
 - Particle release patterns
 - Aperture coverings to reduce convective/radiative losses
 - Closed-loop particle mass flow control for T_{out}
 - Particle feed system
- Particle Storage
 - Demonstrate transient operation at scale with less than 1% heat loss per day
 - Filling and discharging with mass flow control

Gaps and Needs

- Particle Heat Exchanger
 - SuNLaMP project FY16 – FY18
 - Design, build, and test 100 kW particle-sCO₂ heat exchanger
 - Babcock & Wilcox, Solex Thermal Science, Vacuum Process Engr.
 - High pressure sCO₂ (≥ 20 MPa)
 - $T_p > 750$ C
- Particle lift
 - Demonstrate insulated lift operation with low friction (high efficiency) at high particle flow rates (>100 kg/s, >400 tons/hr)
- Particles
 - Reduce abrasion and particle wear
 - Reduce particle loss through aperture
 - Maintain high solar absorptance / reduce thermal emittance



Other Particle Receiver Demonstrations and R&D

300 kW_t Particle Receiver System – King Saud Univ.

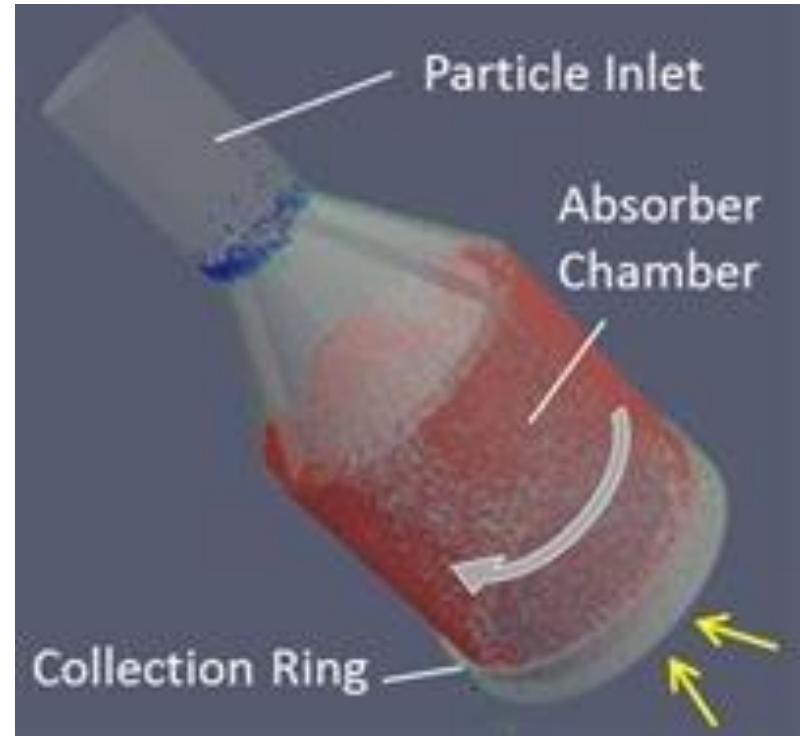
Professor Hany Al-Ansary



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

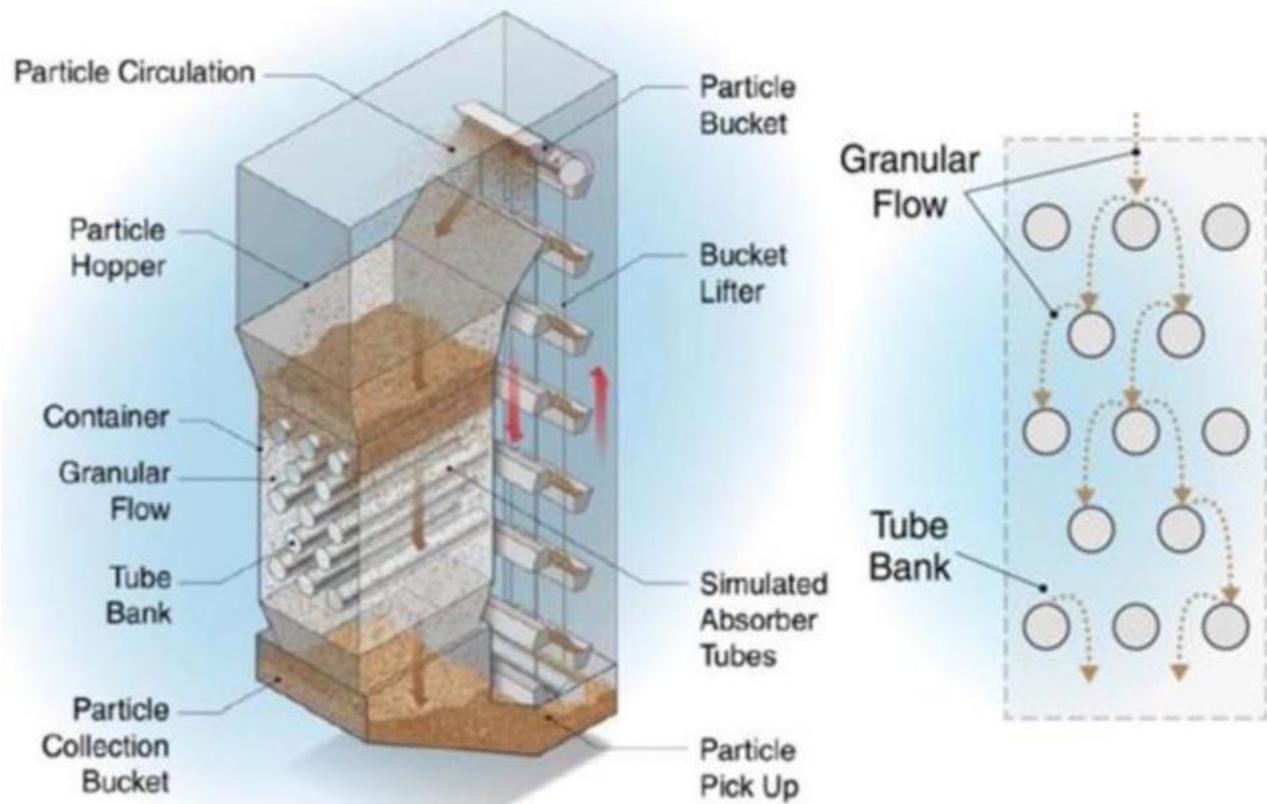
DLR – Centrifugal Particle Receiver

- 15 kW_{th} prototype tested
- 900 C particle temperature at 670 kW/m²
 - 75% efficiency



NREL – Enclosed particle receiver with light trapping

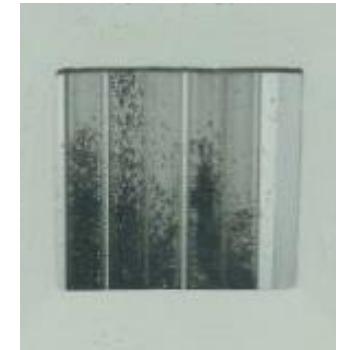
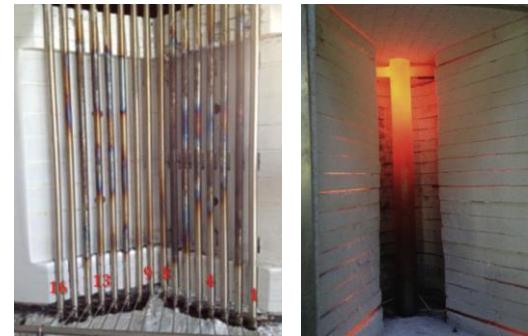
- Particles flow inside enclosure around tubes
- Light penetrates inside tubes



Martinek & Ma (2015)

Fluidized Tubular Particle Receiver

- Flamant et al. – 1980's – present
 - Fluidized particles in opaque tubes
 - 150 kW_{th} pilot tests (1 MW solar furnace)
 - Efficiency 50 – 90%, 585 – 720 C
- Bai et al. (2014) and Matsubara et al. (2015)
 - Fluidized particles in quartz tubes to heat air
- 2 MW beam-down fluidized sand/steam power plant in Sicily, Italy
 - <http://helioscsp.com/concentrated-solar-power-plant-begins-operation-in-italys-sicily/>



Acknowledgments



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- **DLR**
 - Birgit Gobereit, Lars Amsbeck, Reiner Buck

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