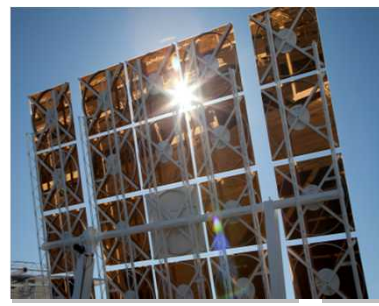
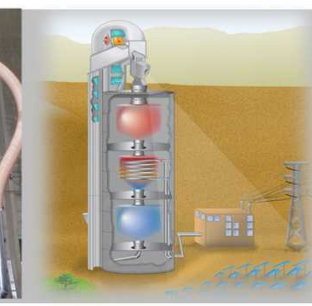
SAND2016-10120C

Highlights of the High-Temperature Falling Particle Receiver Project: 2012 - 2016

Exceptional service in the national interest

Sandia National Laboratories






Contributors:

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

Clifford K. Ho
Sandia National Laboratories
Concentrating Solar Technologies

SAND2016-5660 PE

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Overview

- Introduction
- Particle Receiver System
- On-Sun Testing
- Findings and Path Forward

Motivation

- Higher Efficiency Electricity Production
  - Supercritical CO_2 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

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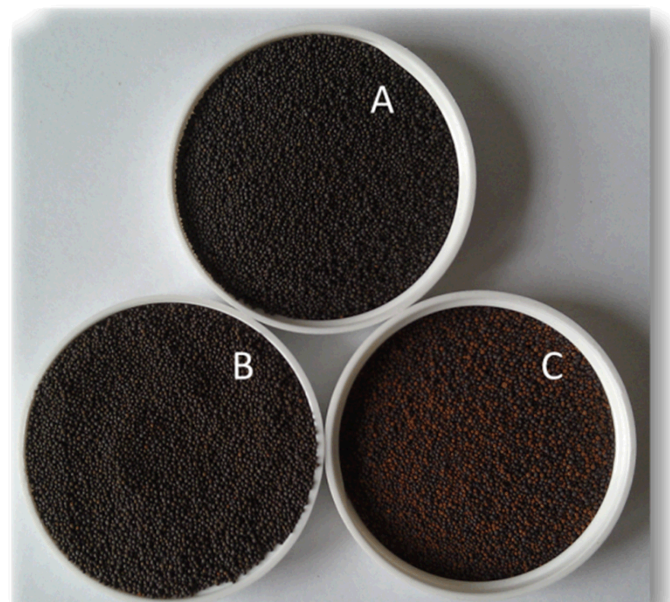
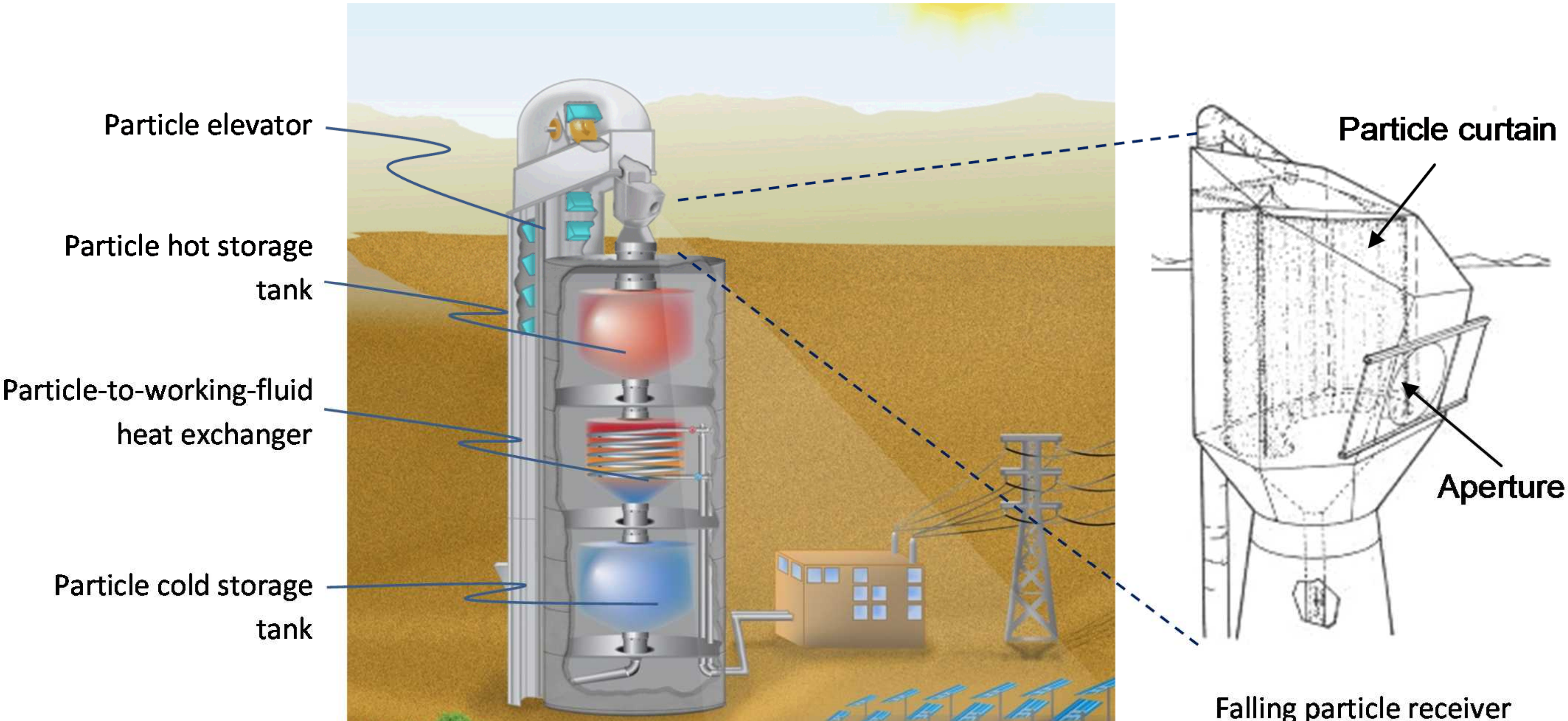
- Direct heating of particles
  - Higher temperatures than conventional molten nitrate salts
    - Enable more efficient power cycles
  - Higher solar fluxes for increased receiver efficiency
- Direct storage of hot particles
  - Reduced costs

⇨ particle Power



CARBO ceramic particles (“proppants”)

High Temperature Falling Particle Receiver
(DOE SunShot Award 2012 - 2016)



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

Overview

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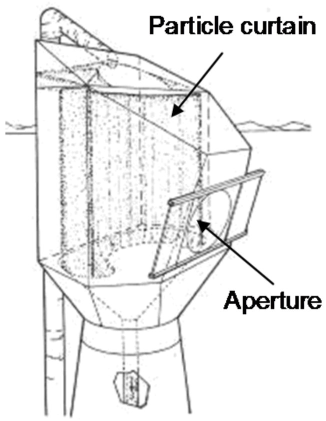
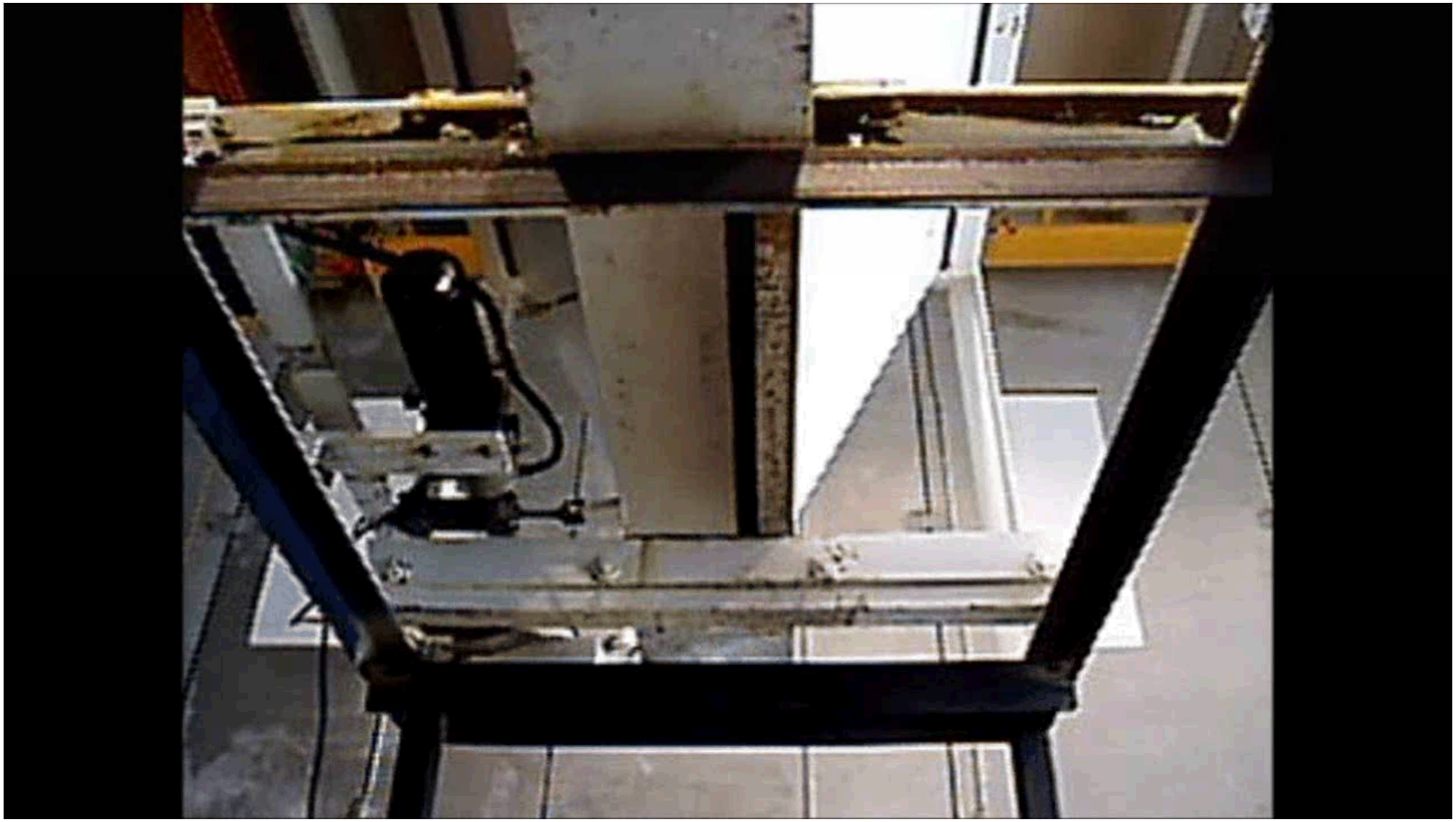
Receiver

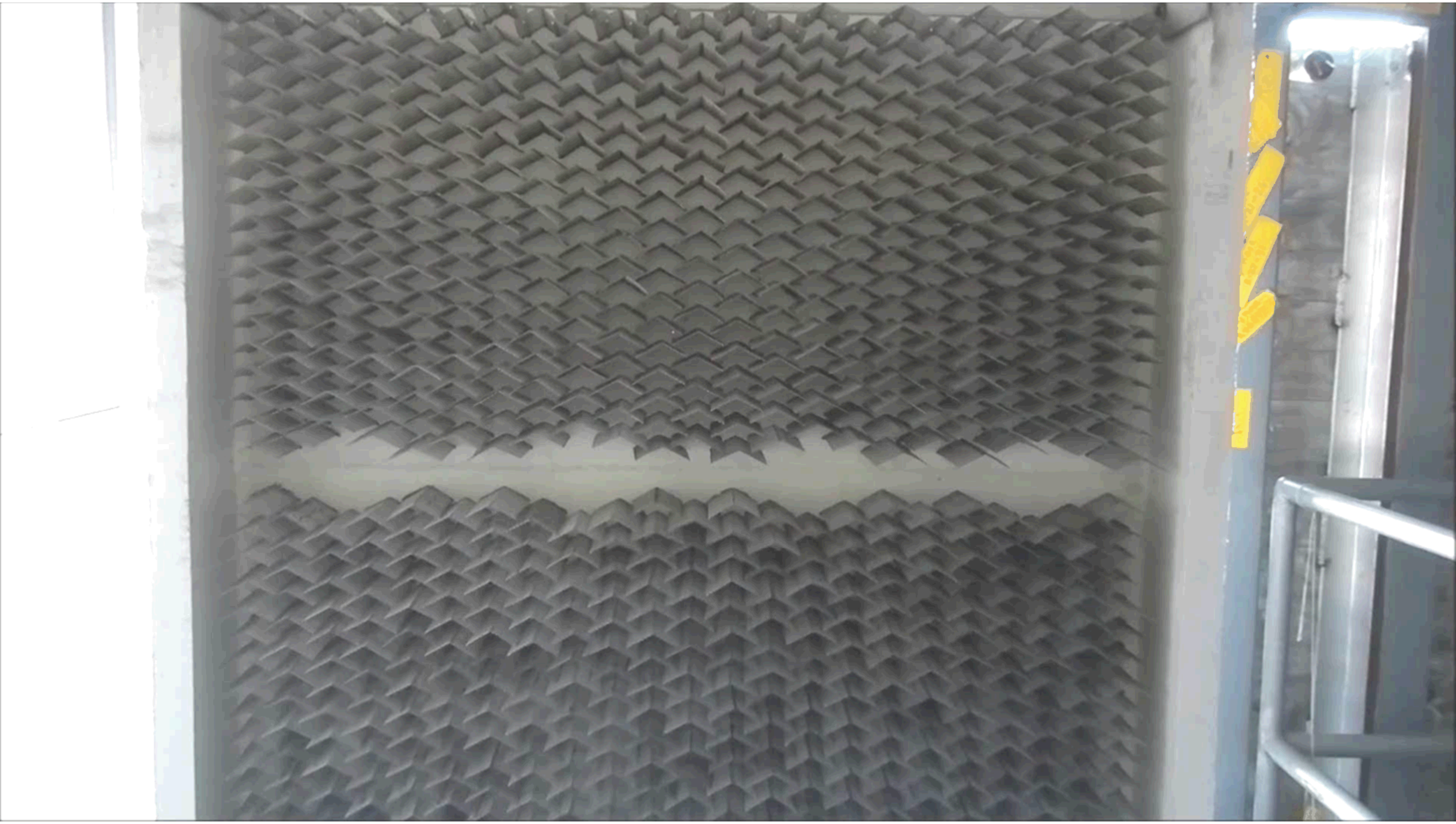
Free-Fall vs. Obstructed Flow



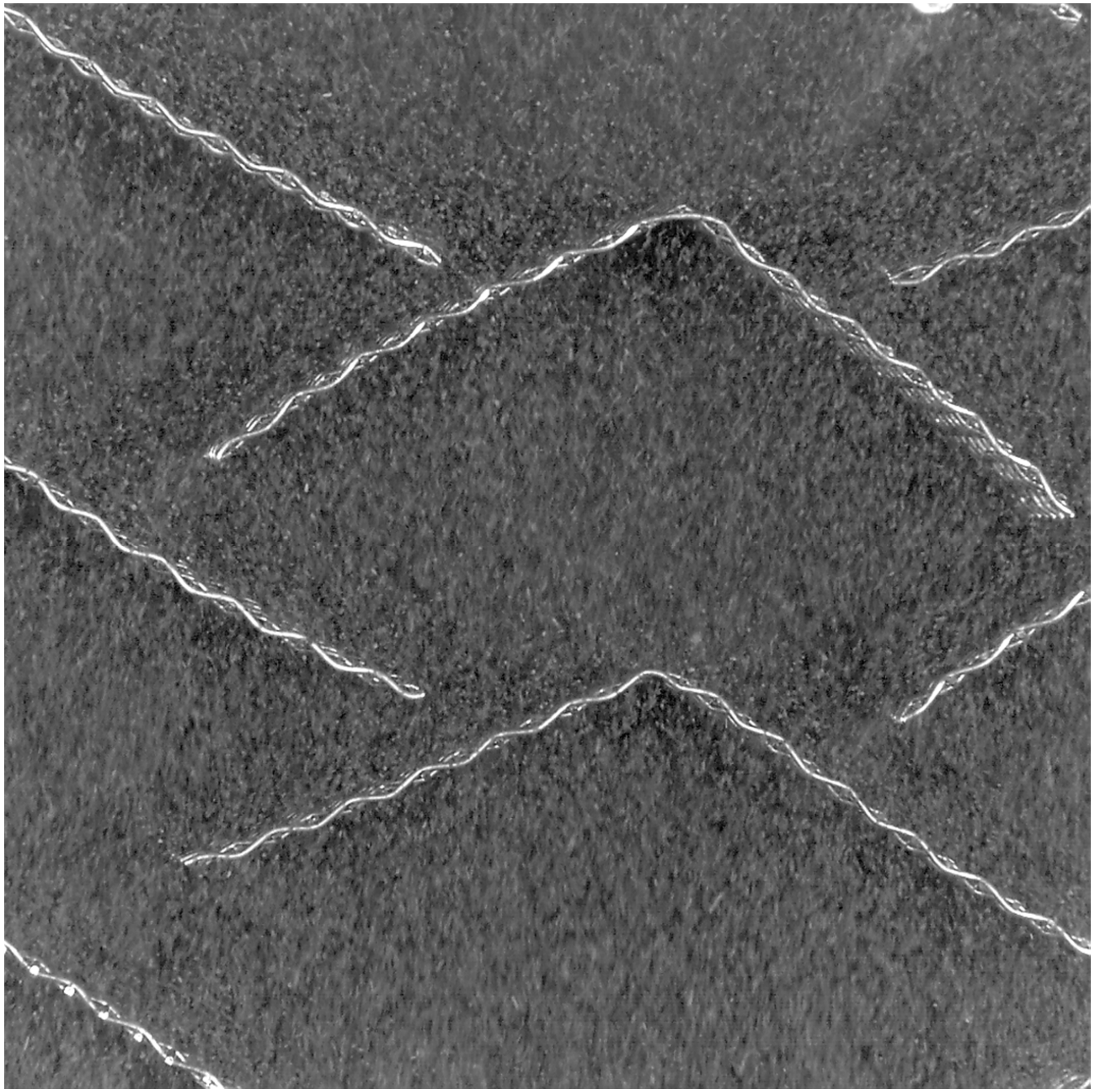
Particle Receiver Designs – Free Falling



Particle Receiver Designs – Pachinko



Particle Flow over Chevron Meshes

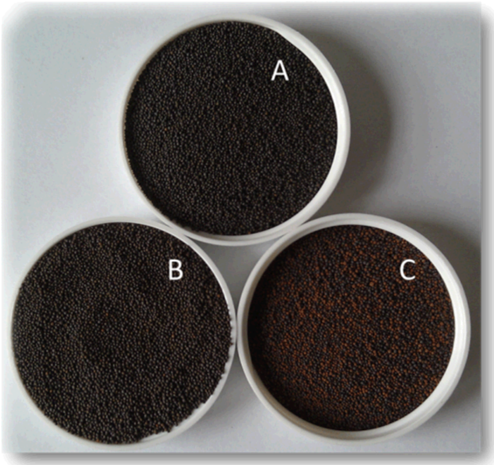


Pros: particle velocity reduced for increased residence time, heating, and flow control

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

Georgia Tech and Sandia National Labs

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.

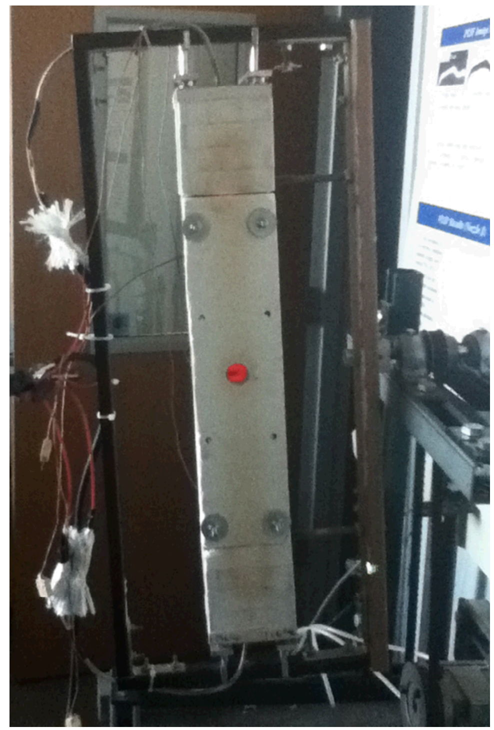
**Q is assumed to be 6×10^5 W/m^2 and T is assumed to be 700 °C (973 K): $\eta_{sel} = \frac{\alpha_s Q - \varepsilon \sigma T^4}{Q}$

Siegel et al. 2015, The Development of Direct Absorption and Storage Media for Falling Particle Solar Central Receivers, *ASME J. Solar Energy Eng.*, **137**(4)

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.

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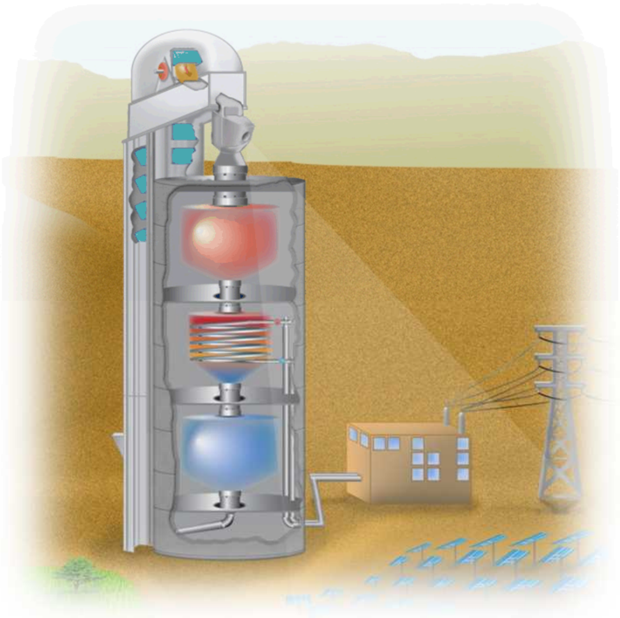
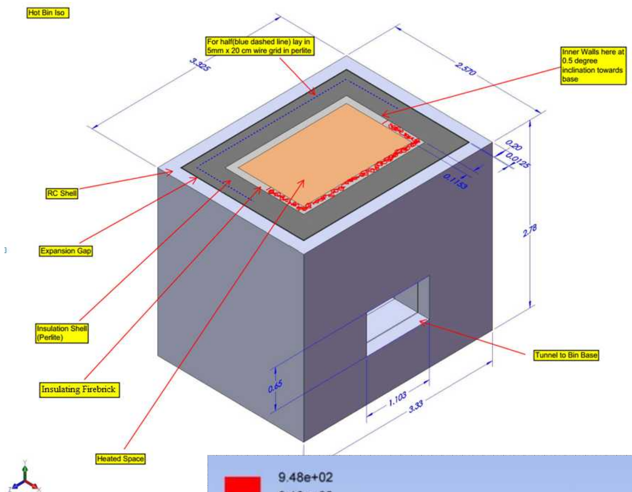
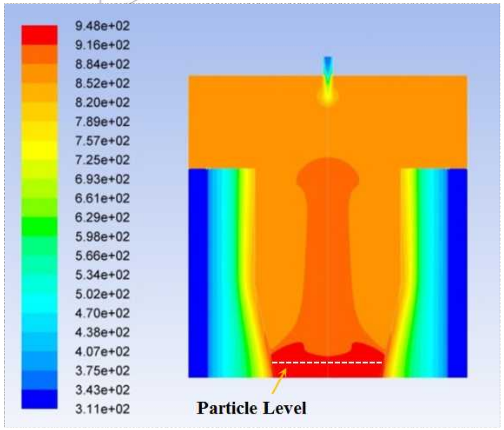
Balance of Plant



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

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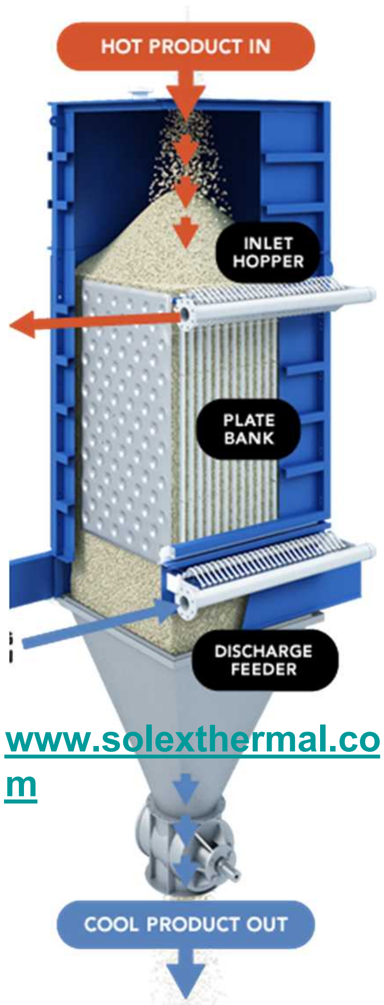
- Evaluation of heat transfer coefficients & particle flow



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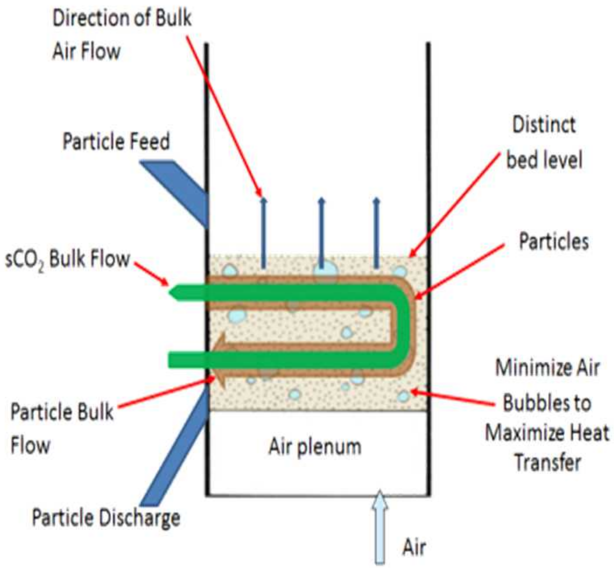
VPE VACUUM PROCESS ENGINEERING

<u>Moving Packed-Bed</u>
Shell-and-Tube
Shell-and-Plate

B&W the babcock & wilcox company

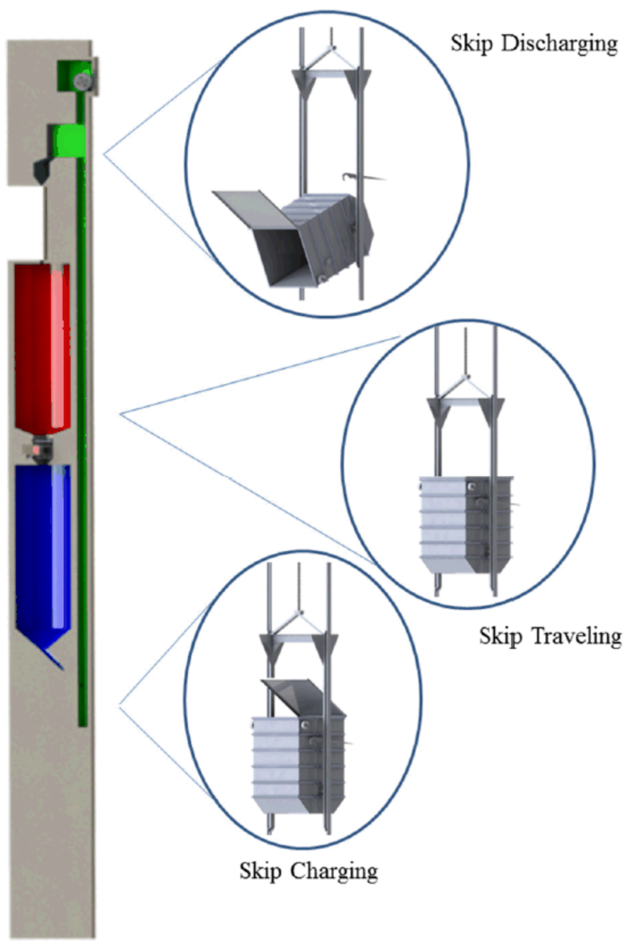
Fluidized-Bed Heat Exchanger



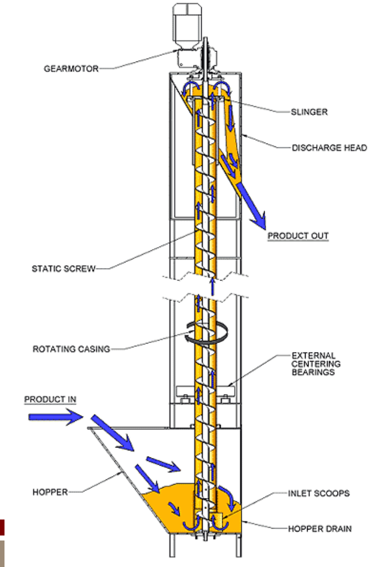
Golob et al., 2013, "Serpentine Particle-Flow Heat Exchanger with Working Fluid, for Solar Thermal Power Generation," SolarPACES 2013

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 – 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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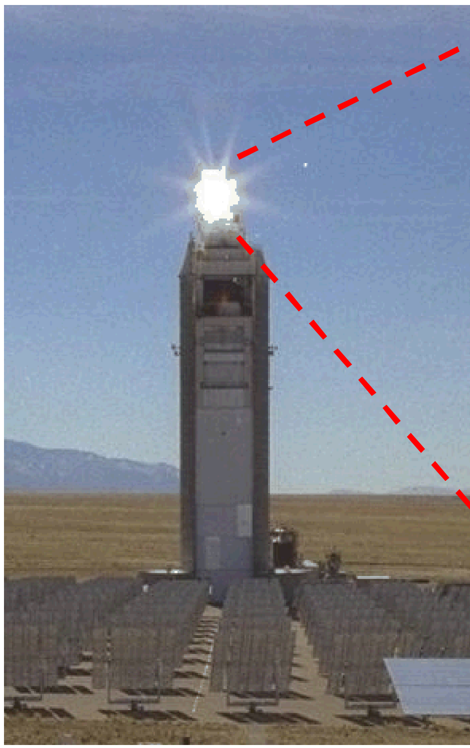
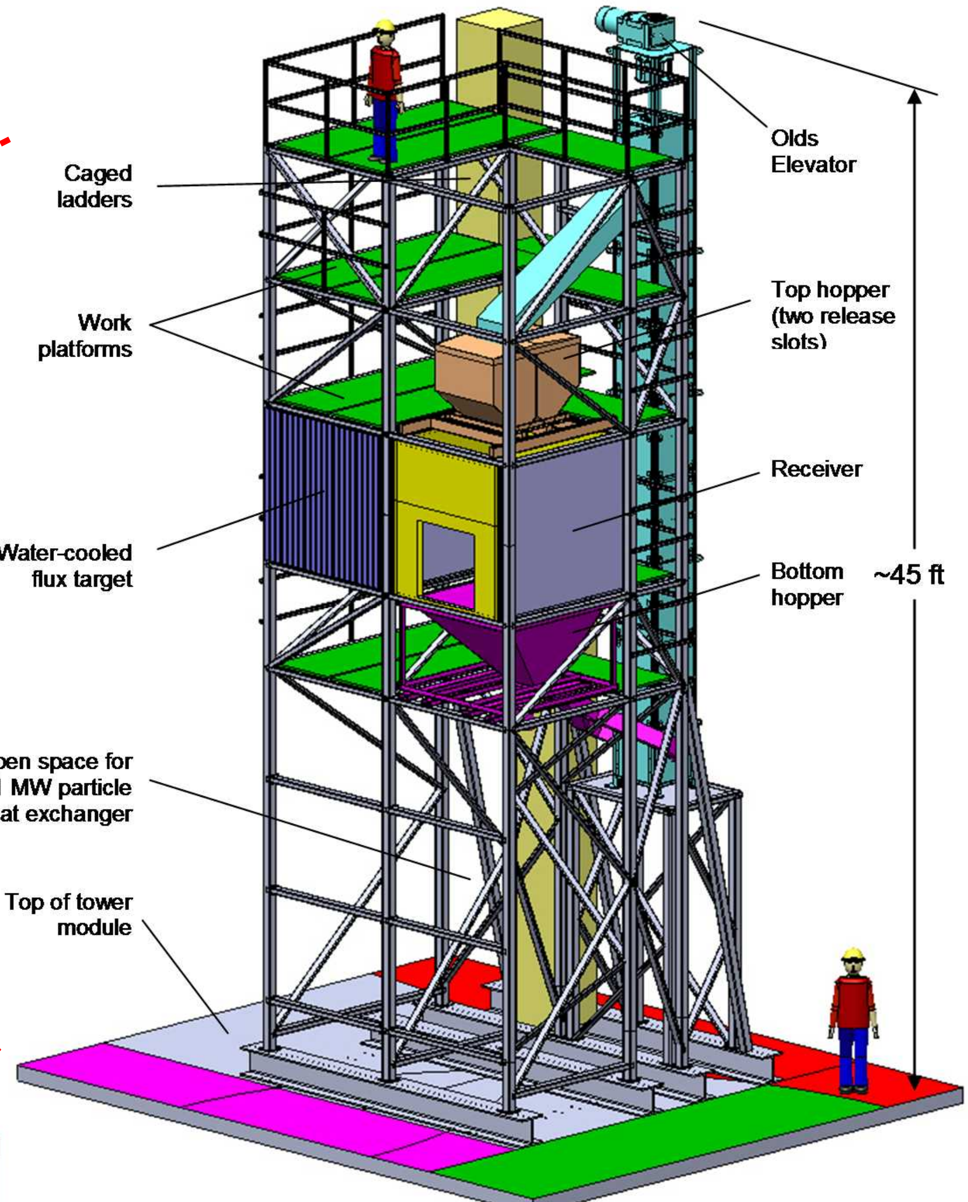
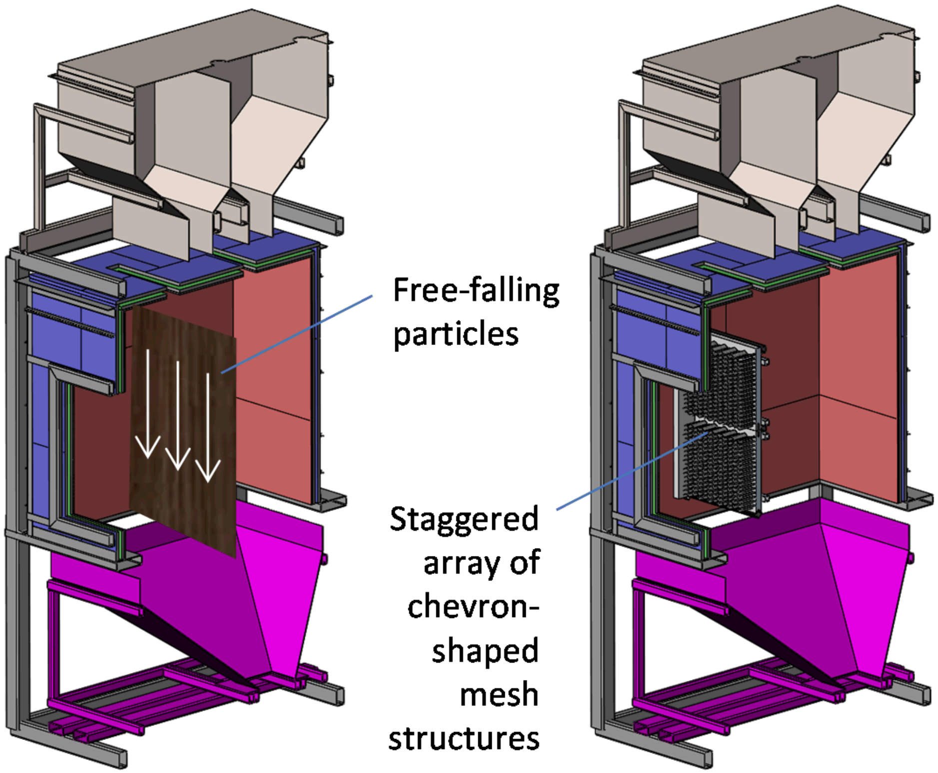
Prototype System Design





Particle Release Configurations



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)

Overview

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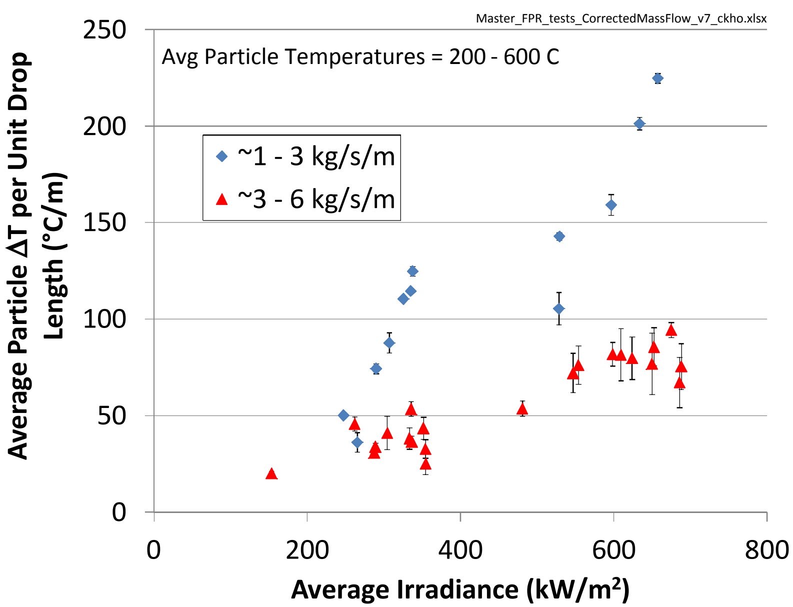
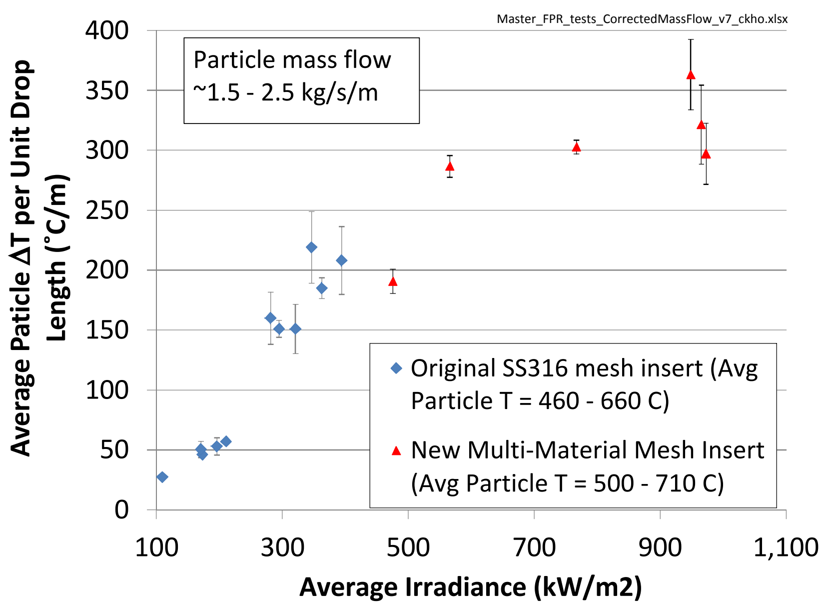
Findings

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



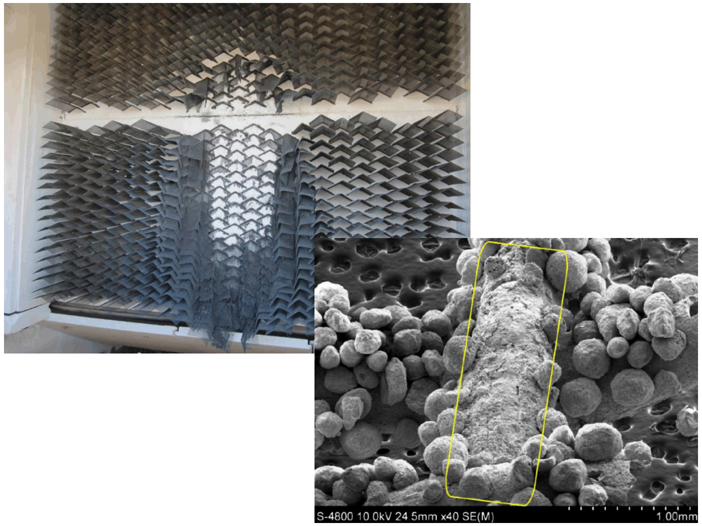
Free-Fall

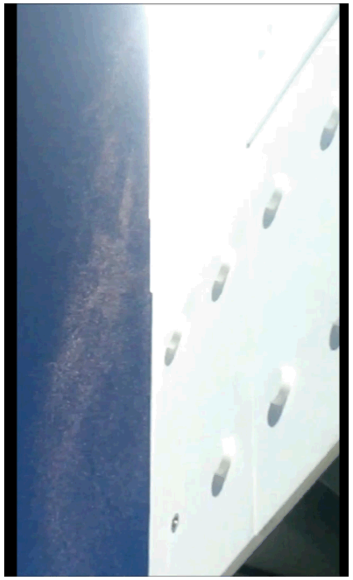


Obstructed-Flow

Lessons Learned

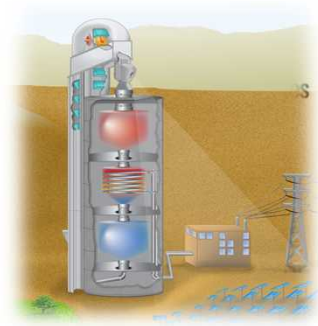
- Mesh materials (SS316) showed signs of wear
  - Evaluate alternative alloys or ceramics
- Particle mass flow was reduced at higher temperatures
  - Two reasons:
    - Narrowing of discharge slot
    - Higher particle/wall friction coefficient
  - Need active particle mass flow control and monitoring
- 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





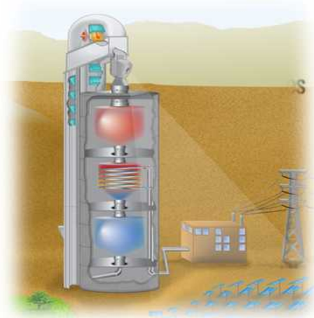
Particle loss from aperture during on-sun test

Path Forward



- 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

Path Forward



- Particle Heat Exchanger
  - DOE 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

Acknowledgments

Award # DE-EE0000595-1558

- **Sandia National Labs**
  - Josh Christian, Daniel Ray, JJ Kelton, Kye Chisman, Bill Kolb, Ryan Anderson, Ron Briggs
- **Georgia Tech**
  - Sheldon Jeter, Said Abdel-Khalik, Matthew Golob, Dennis Sadowski, Jonathan Roop, Ryan Knott, Clayton Nguyen, Evan Mascianica, Matt Sandlin
- **Bucknell University**
  - Nate Siegel, Michael Gross
- **King Saud University**
  - Hany Al-Ansary, Abdelrahman El-Leathy, Eldwin Djajadiwinata, Abdulaziz Alrished
- **DLR**
  - Birgit Gobereit, Lars Amsbeck, Reiner Buck

Backup Slides

Other Particle Receiver Demonstrations and R&D

300 kW_t Particle Receiver System

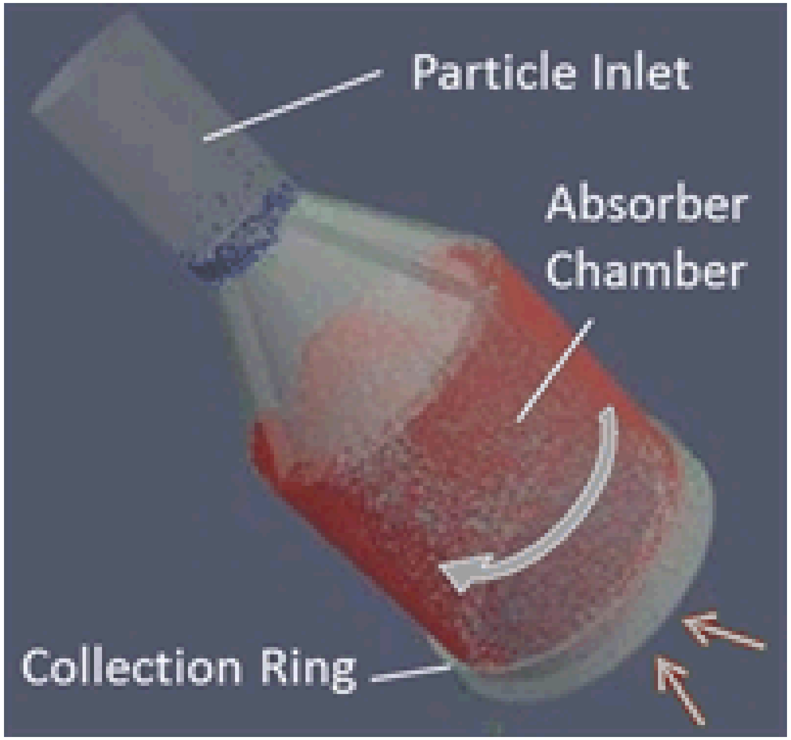
King Saud University

Professor Hany Al-Ansary

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

DLR – Centrifugal Particle Receiver

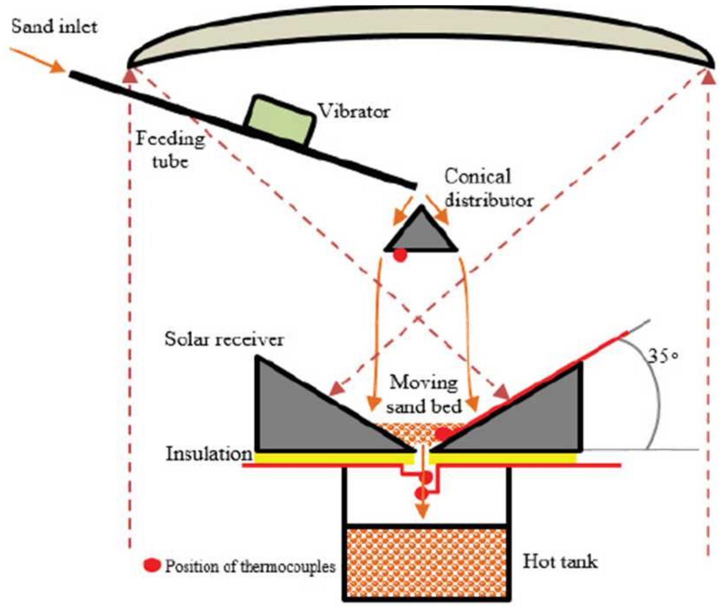
- 15 kW_{th} prototype tested
- 900 C particle temperature at 670 kW/m^2
  - 75% efficiency



Beam-Down Particle Receiver

Masdar and PROMES CNRS

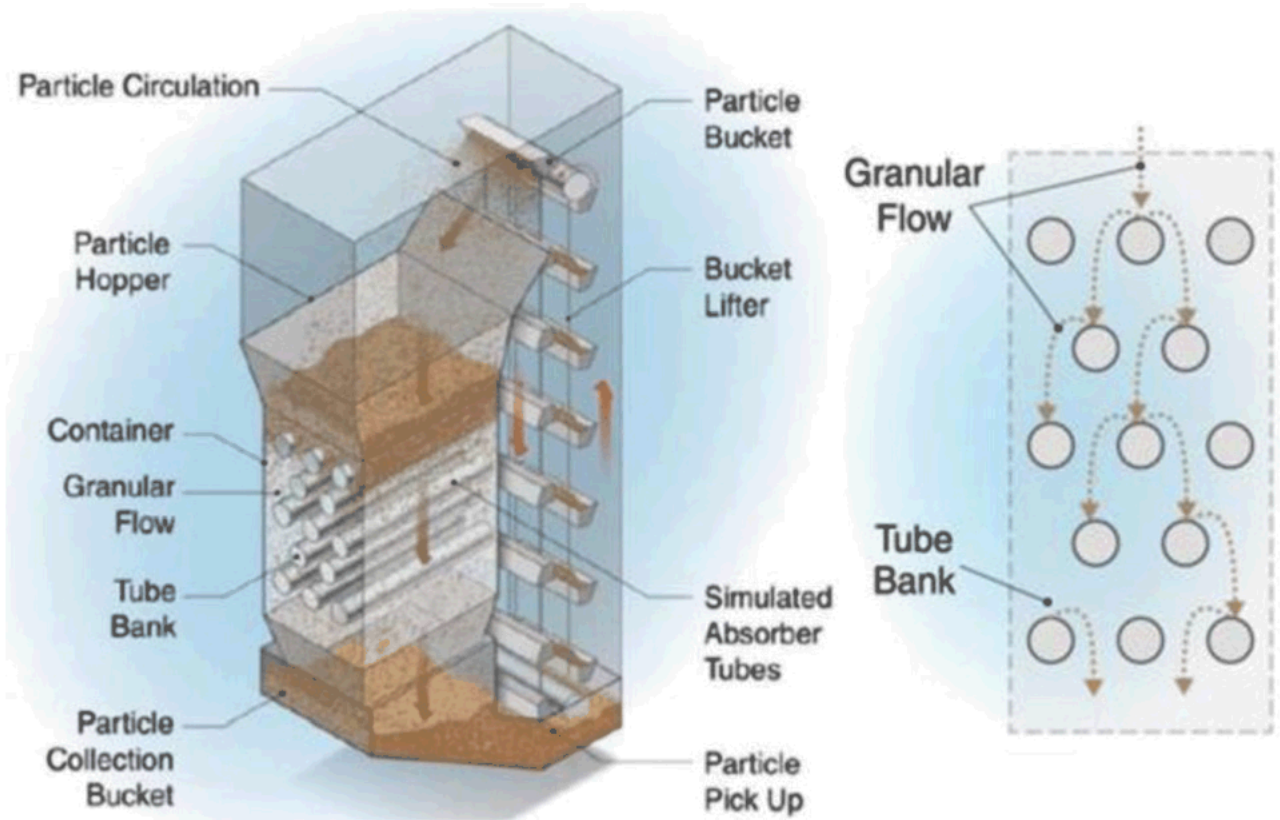
- Iniesta et al. (2015)
- Beam-down sand receiver and storage system
  - Achieved ~600 C with 2 kW solar furnace and < 0.5 g/s



Position of thermocouples

NREL – Enclosed particle receiver with light trapping

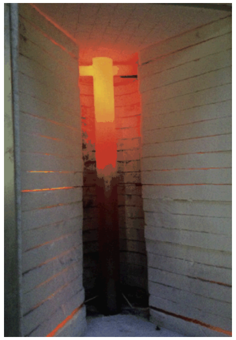
- Particles flow inside enclosure around tubes
- Light penetrates inside tubes



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/

Countries Pursuing Particle Receiver Systems

- U.S.
- Germany
- France
- UAE
- China
- Italy
- Australia
- Switzerland
- Spain
- Japan