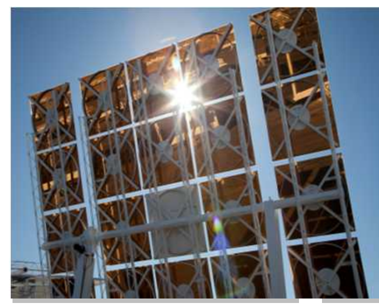
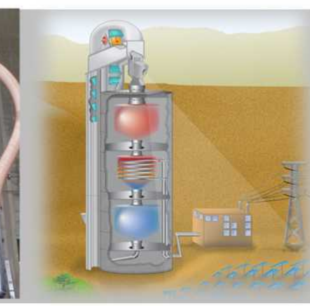
SAND2015-8638C

High-Temperature Falling Particle Receiver Project Overview

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

SAND2015-7383 PE

U.S. DEPARTMENT OF ENERGY

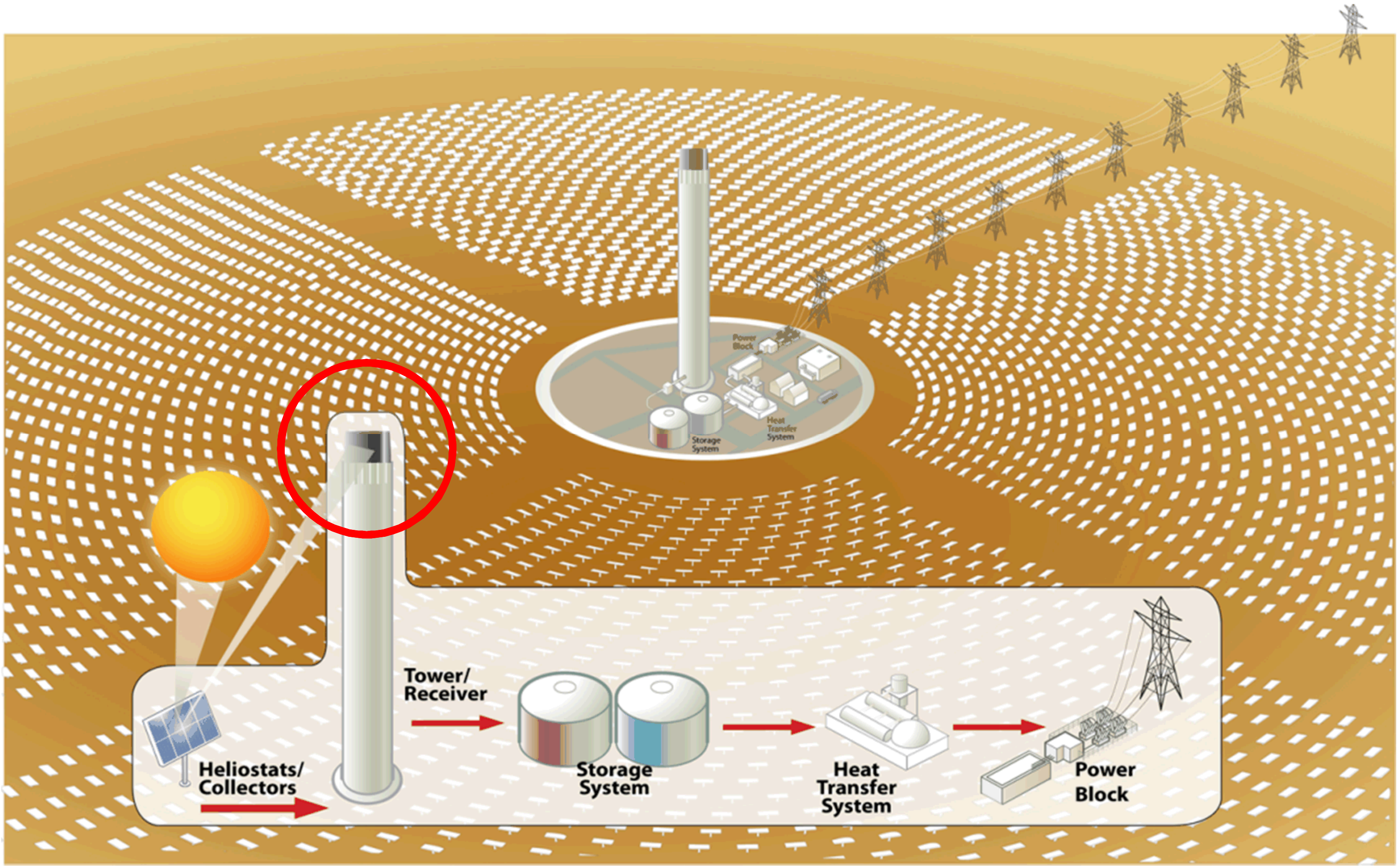
NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

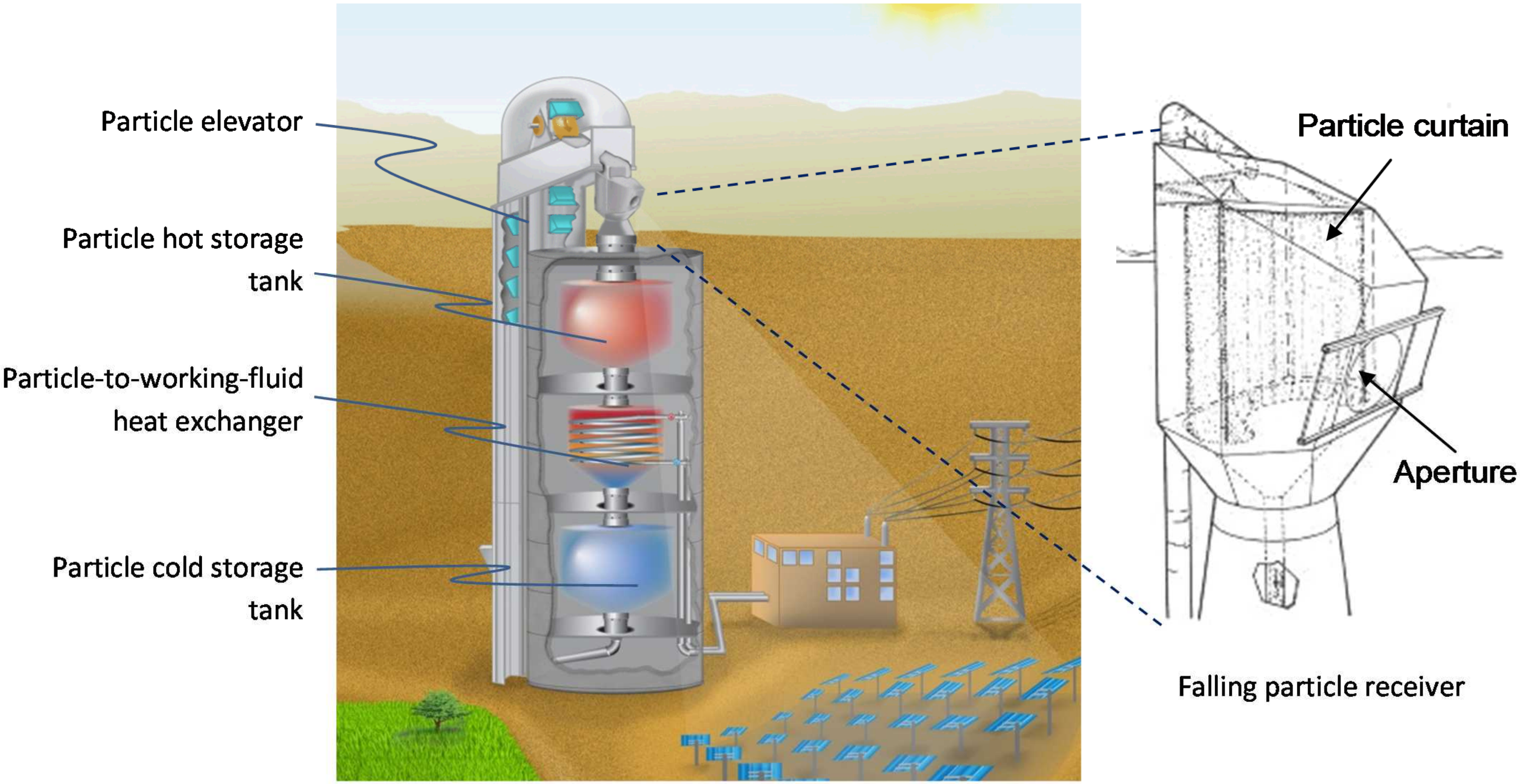
Overview

- Introduction and Objectives
- Particle Receiver System
- On-Sun Testing
- Conclusions and Next Steps

Introduction

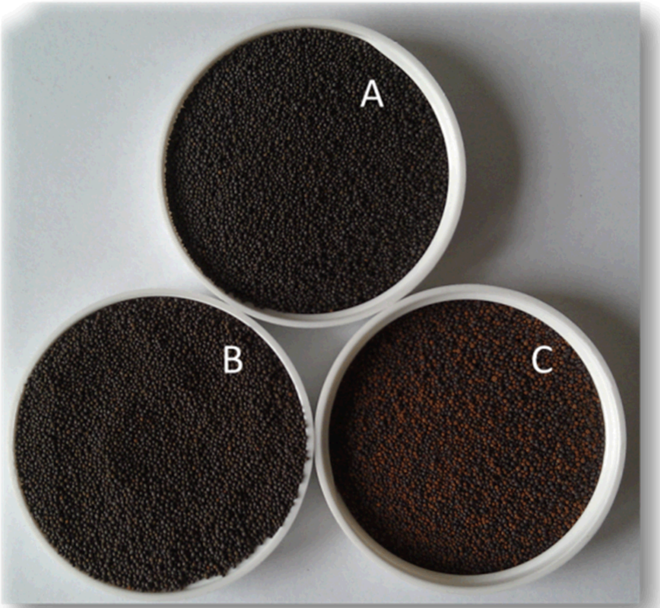


High Temperature Falling Particle Receiver
(DOE SunShot Award FY13 – FY15)



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”)

General Approach

Phase 1

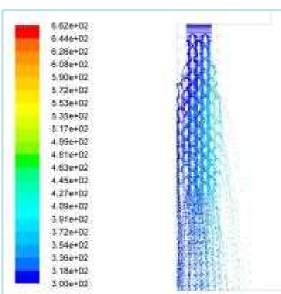
- Modeling, design, proof-of-concept testing

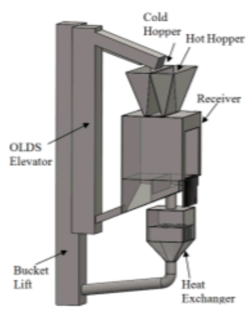
Phase 2

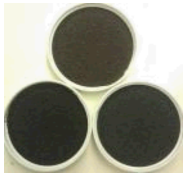
- Component testing, model validation, design optimization

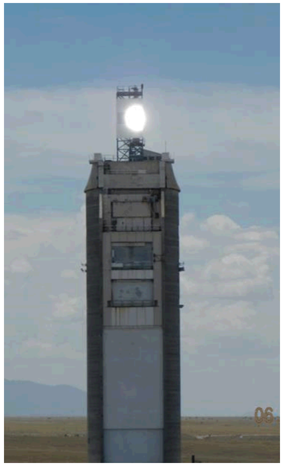
Phase 3

- Prototype development for on-sun testing







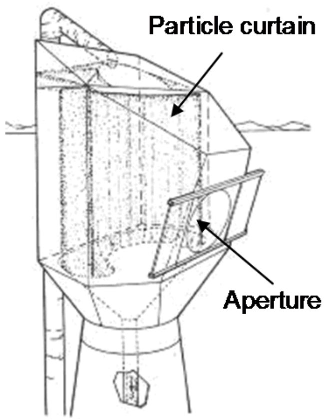


Overview

- Introduction and Objectives
- Particle Receiver System
  - Receiver
  - Particles
  - Balance of Plant
- On-Sun Testing
- Conclusions and Next Steps

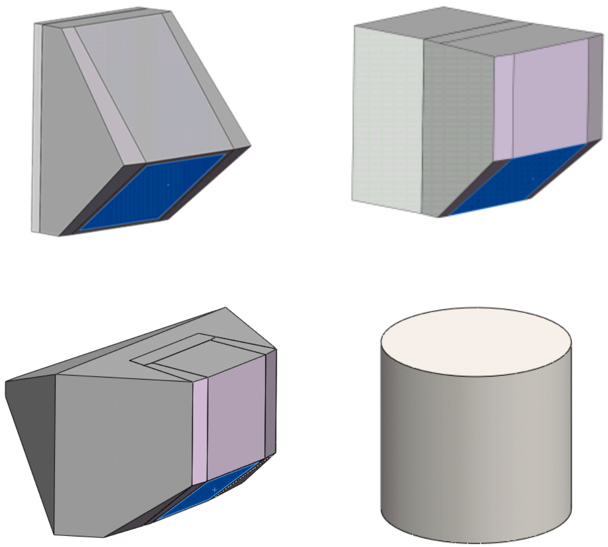
Receiver

Free-Fall vs. Obstructed Flow

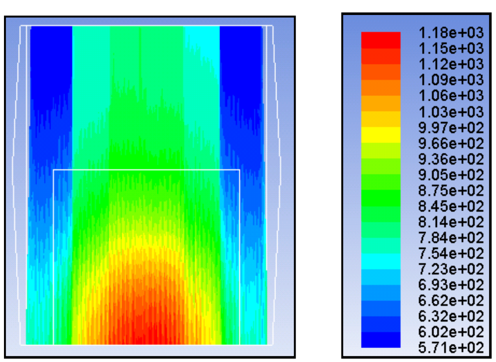


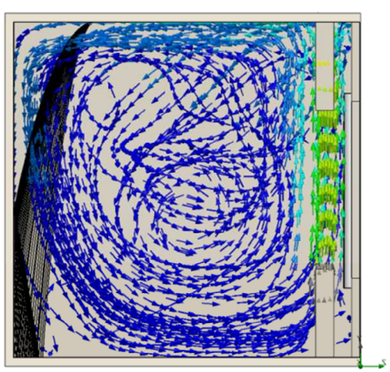
Free-Falling Receiver Designs

Sandia National Laboratories

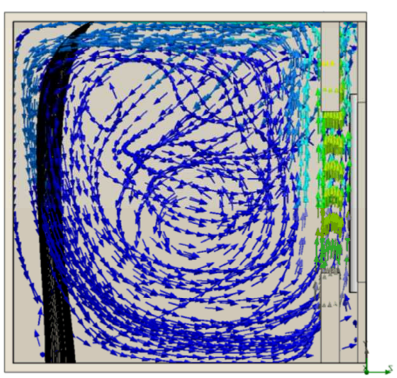


- Developed CFD models to optimize receiver performance
  - ANSYS FLUENT: Radiation, convection, discrete phase particles, turbulence
  - Features modeled
    - Alternative geometries
    - Particle recirculation
    - Air curtain
    - Particle size, mass flow rate, release patterns

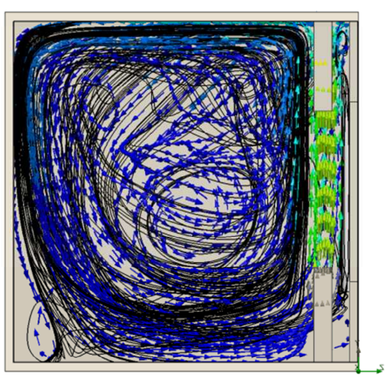




1 mm particle size

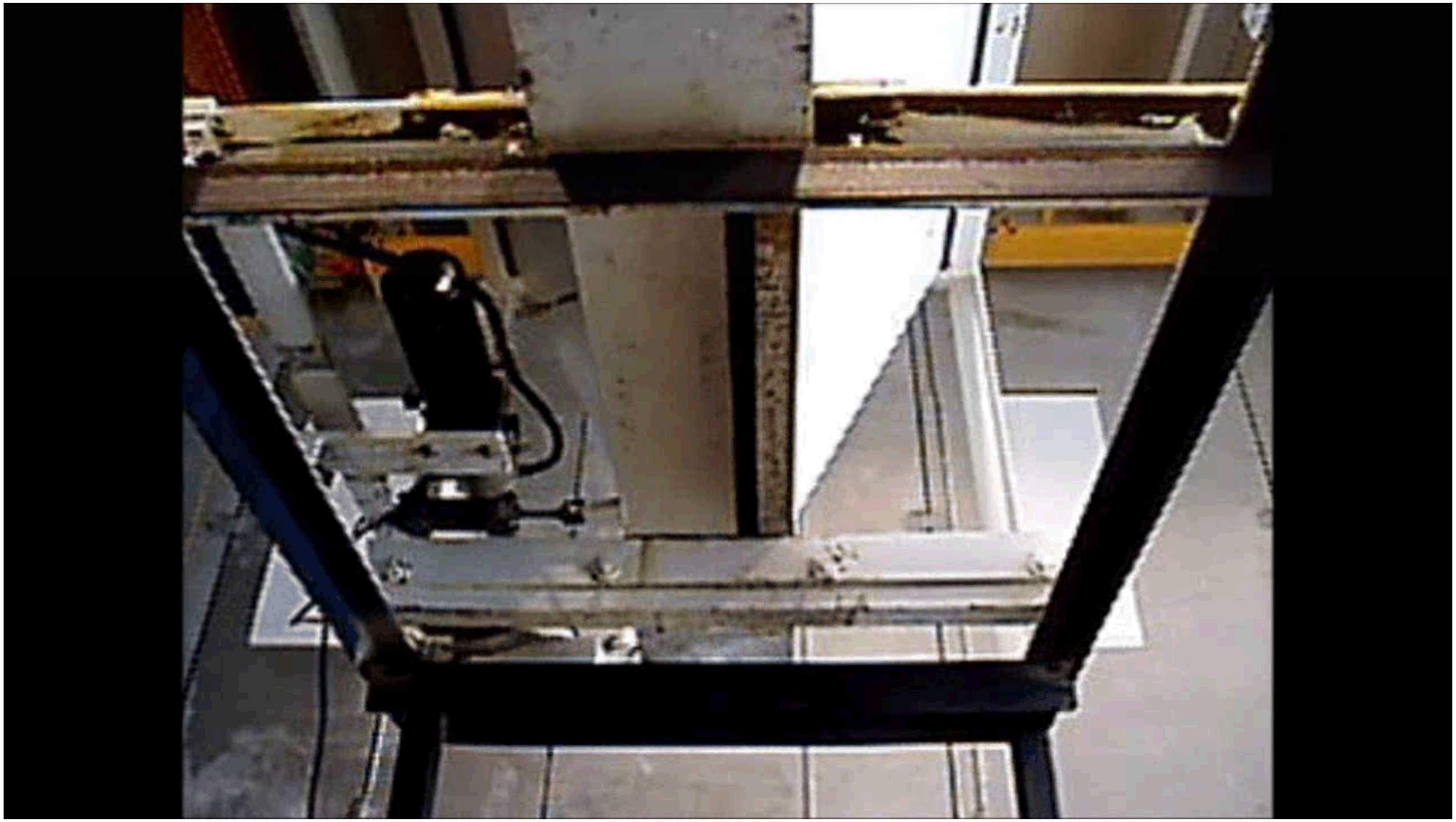


100 μm particle size

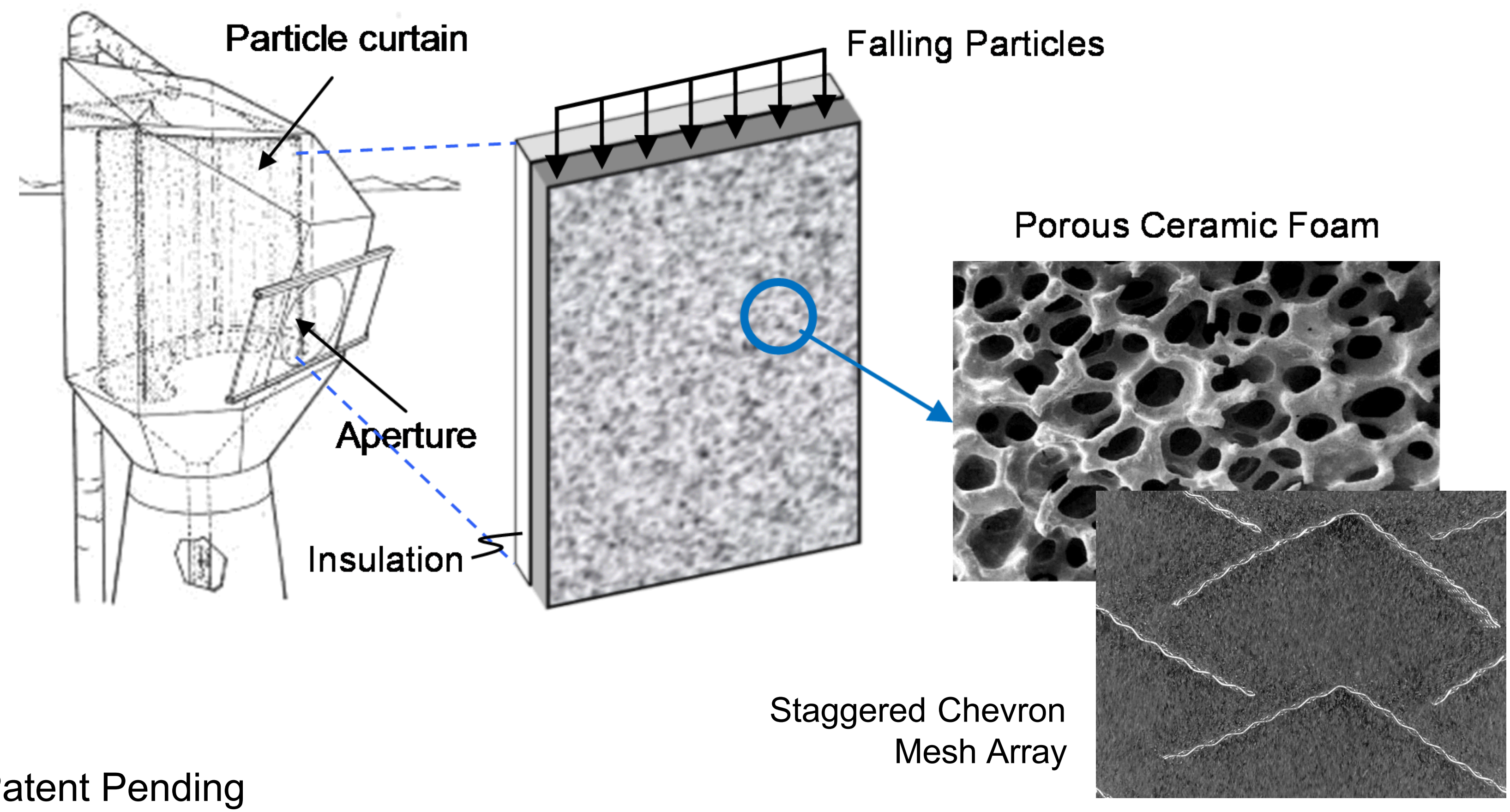


10 μm particle size

Particle Receiver Designs – Free Falling



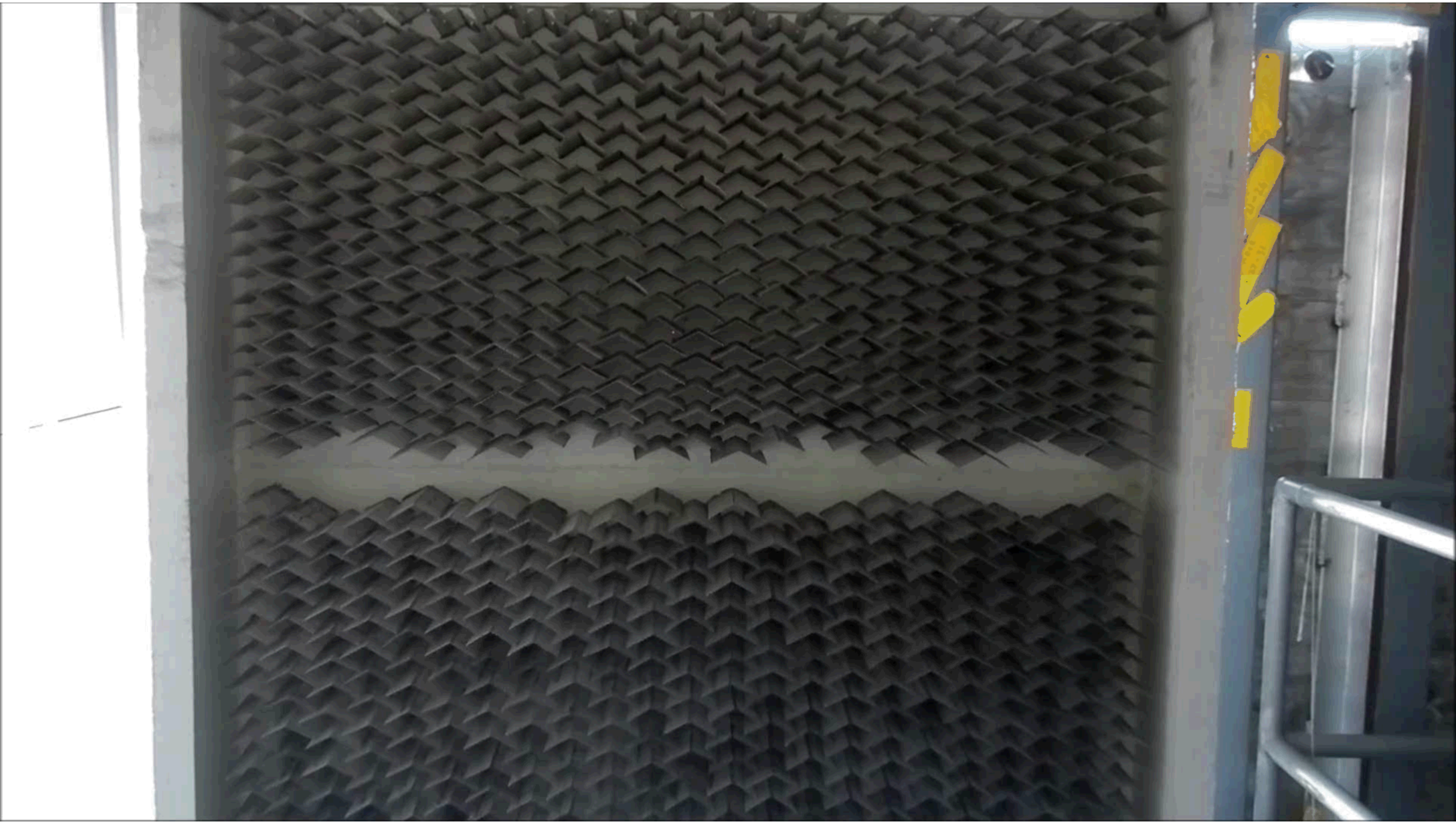
Obstructed Flow Designs



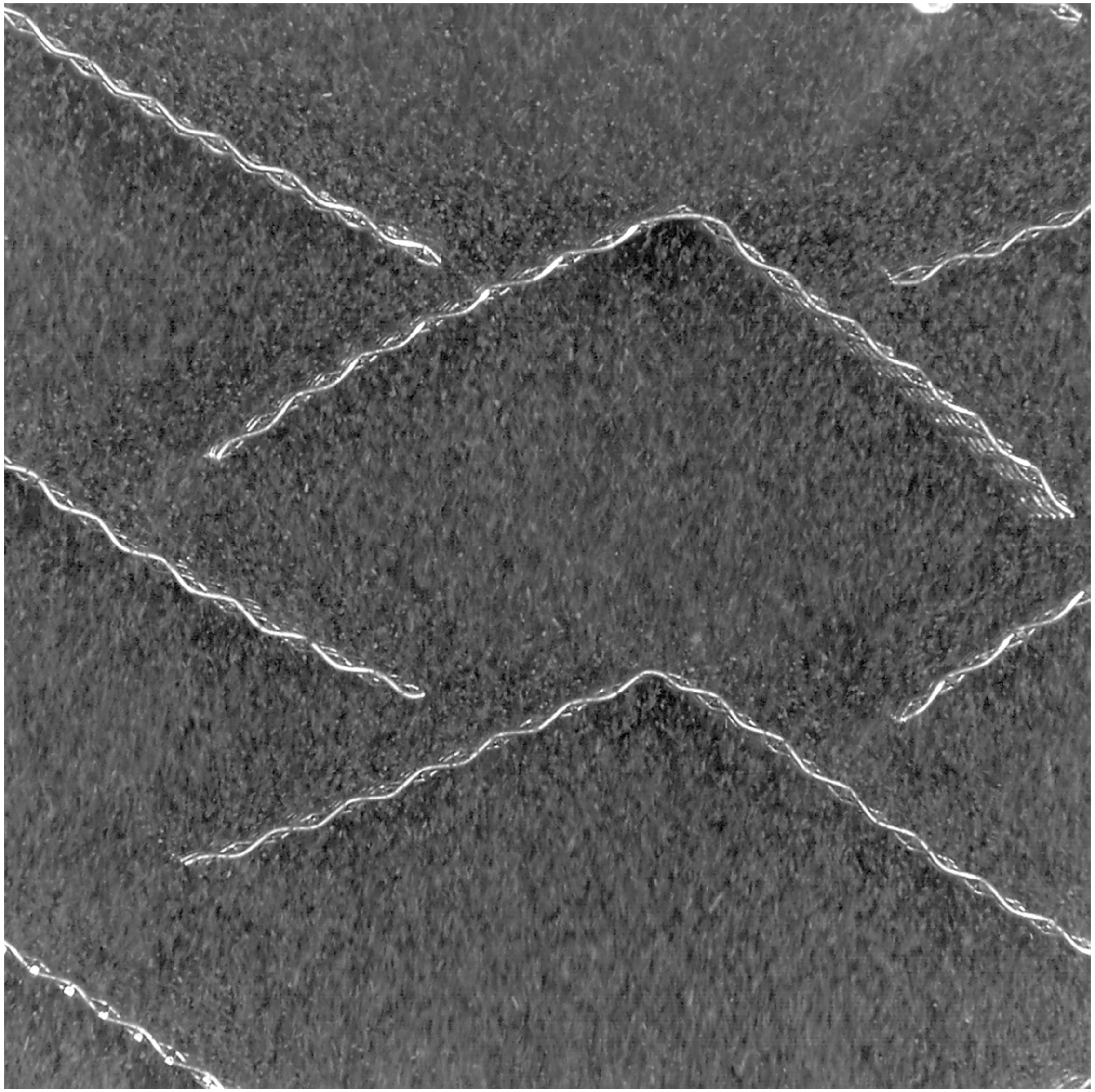
Patent Pending

Al Ansary, H. et al., United States Patent Application 2013/0068217 A1, Solid Particle Receiver with Porous Structure for Flow Regulation and Enhancement of Heat Transfer, K.S. University, March 21, 2013.

Staggered Array of Chevron Mesh Structures



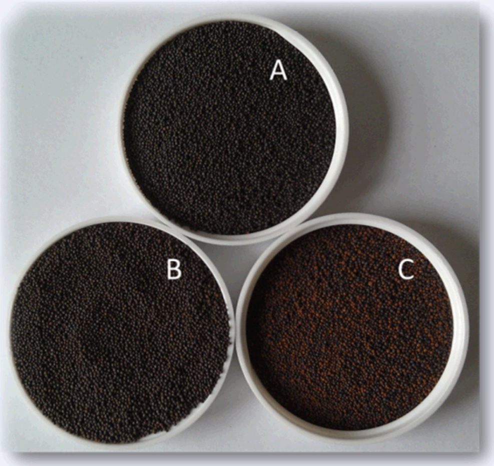
Particle Flow over Chevron Meshes



Pros: particle velocity reduced for increased residence time and heating

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

Particles



Particle Radiative Properties and Rejuvenation

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): $\eta_{sel} = \frac{\alpha_s Q - \varepsilon \sigma T^4}{Q}$

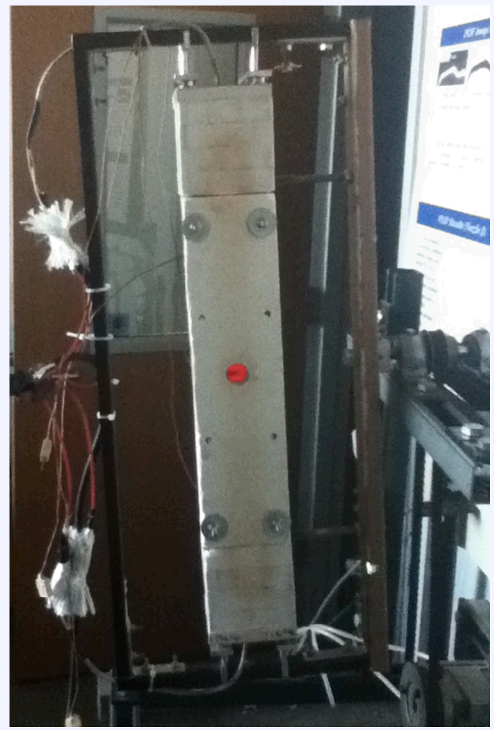
Siegel et al. 2015, The Development of Direct Absorption and Storage Media for Falling Particle Solar Central Receivers, *ASME J. Solar Energy Eng.*, **137**(4)

SunShot U.S. Department of Energy

Particle Durability

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

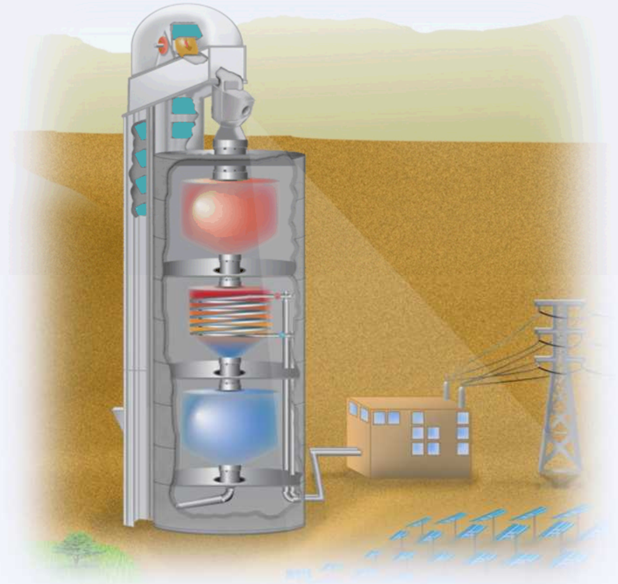
Ambient drop tests at ~10 m



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

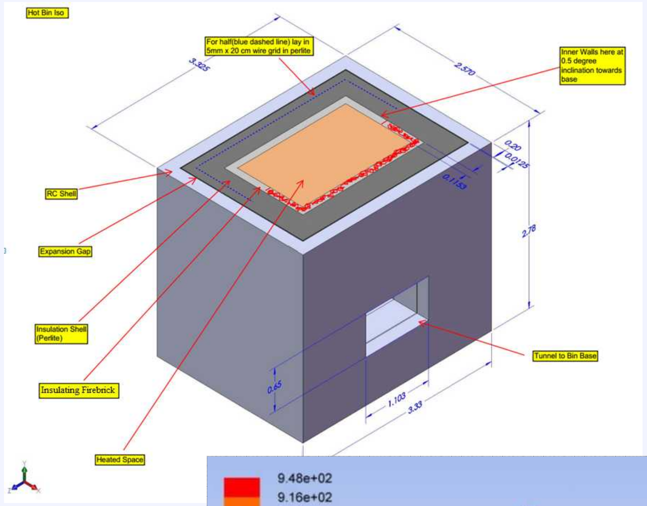
Knott, R., D.L. Sadowski, S.M. Jeter, S.I. Abdel-Khalik, H.A. Al-Ansary, and A. El-Leathy, 2014, *High Temperature Durability of Solid Particles for Use in Particle Heating Concentrator Solar Power Systems*, in *Proceedings of the ASME 2014 8th International Conference on Energy Sustainability*, ES-FuelCell2014-6586,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

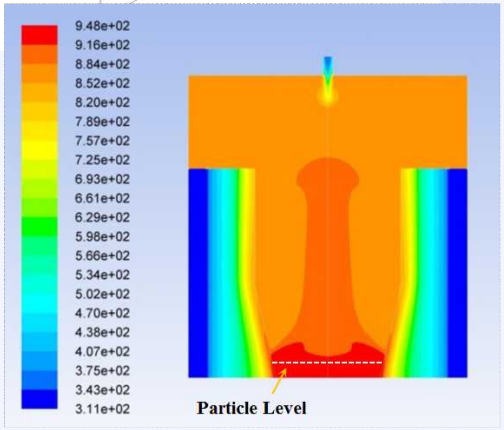
Balance of Plant



Thermal Storage

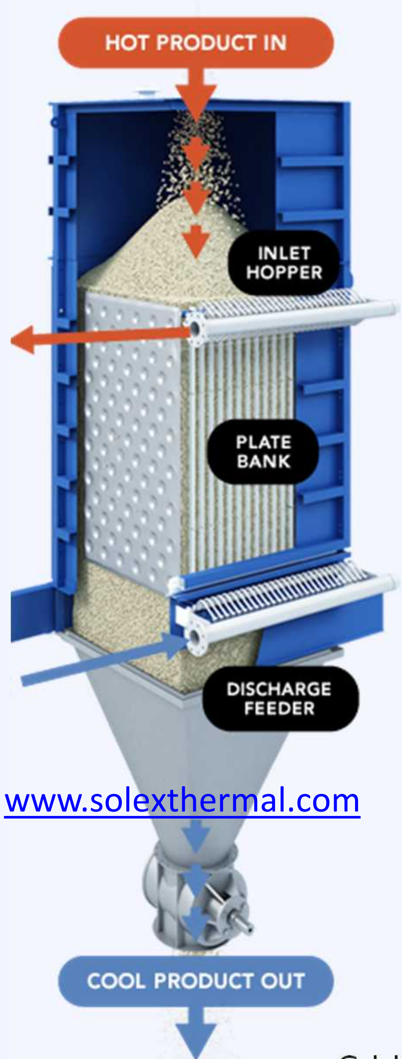
- Experimental evaluation and modeling of prototype thermal energy storage designs





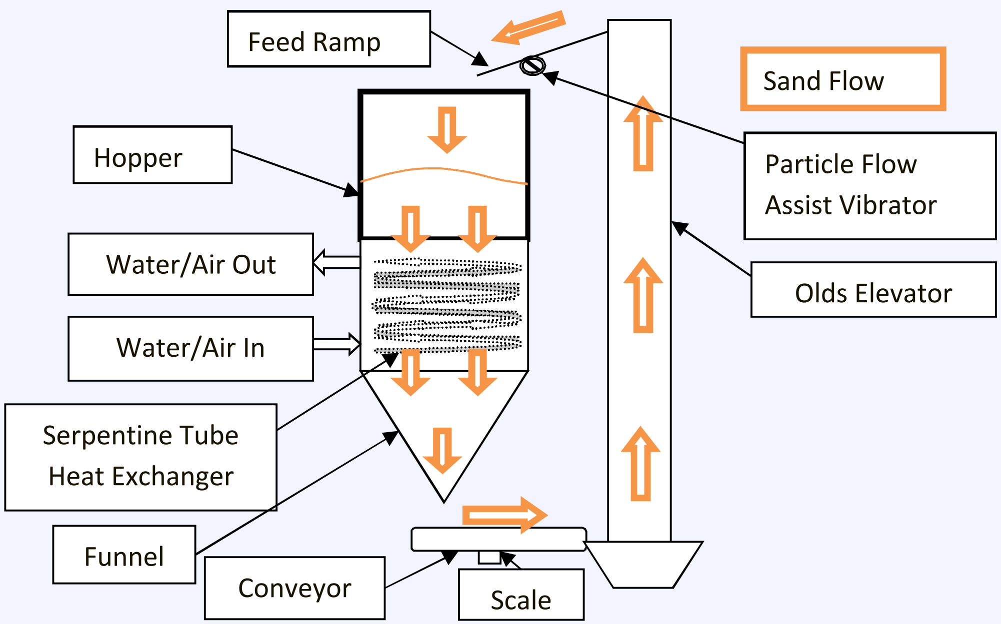
El-Leathy et al., "Experimental Study of Heat Loss from a Thermal Energy Storage System for Use with a High-Temperature Falling Particle Receiver System," SolarPACES 2013

Particle to Working Fluid Heat Exchanger



www.solexthermal.com

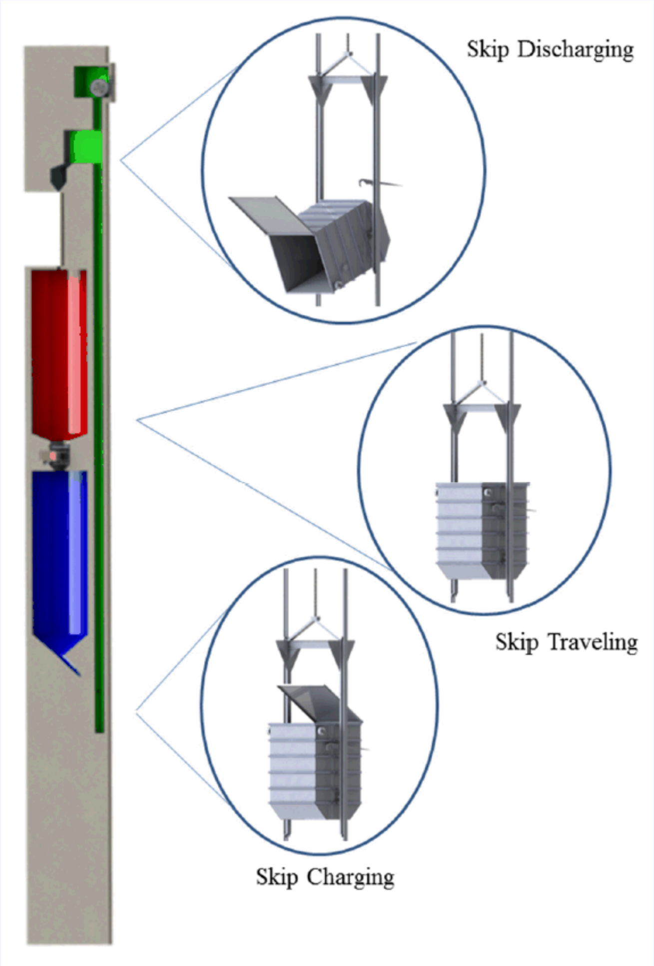
- Experimental evaluation of heat transfer coefficients & particle flow
  - Heat exchanger module designed and instrumented for continuous sand flow over tubes



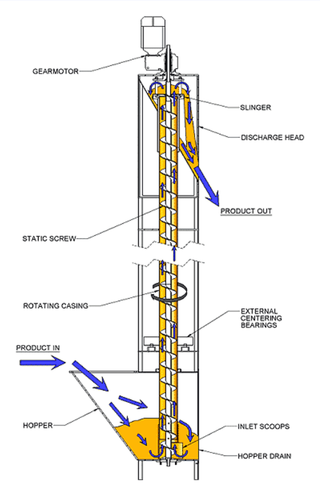
Golob et al., 2013, "Serpentine Particle-Flow Heat Exchanger with Working Fluid, for Solar Thermal Power Generation," SolarPACES 2013

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
    - Up to 10 kg/s/m
    - Operating temperature ~ 500 °C (assumes ΔT during last drop of >200 °C)
  - Different lift strategies evaluated
    - Olds Elevator
    - Screw-type
    - Bucket
    - Mine hoist

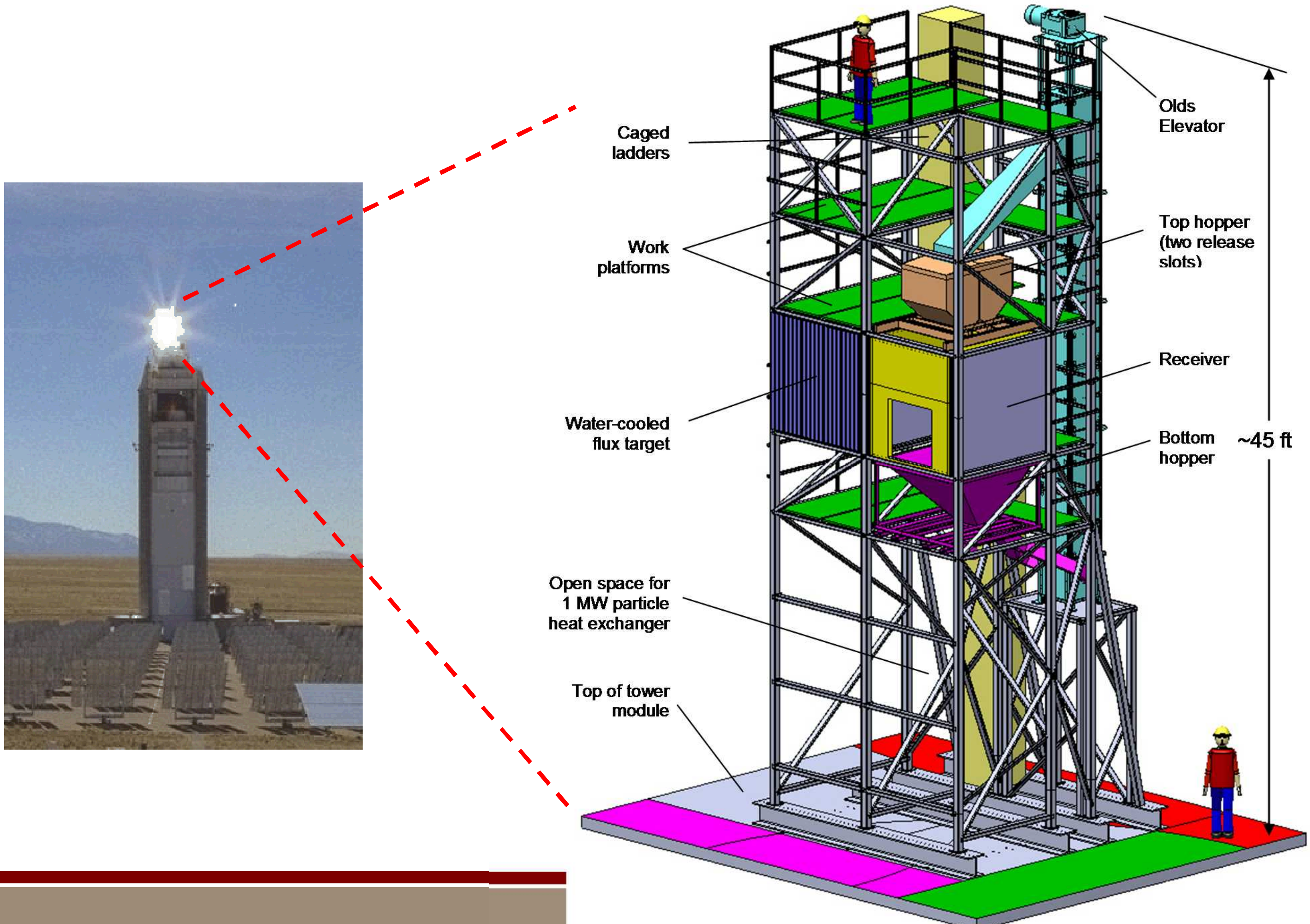


Repole K, Jeter S, "Design and Analysis of a High Temperature Particulate Hoist for Proposed Particle Heating Concentrator Solar Power Systems", Energy Conversion and Management, - Submitted

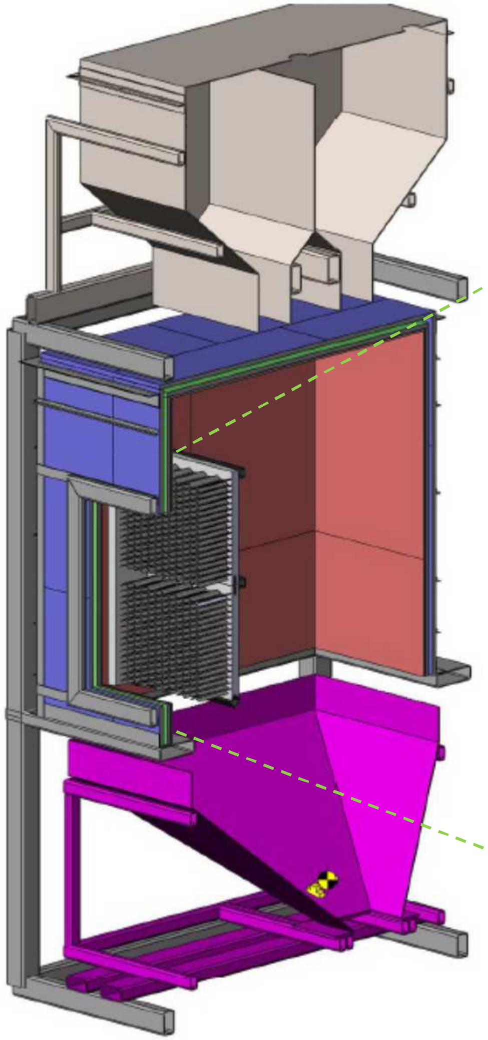
Overview

- Introduction and Objectives
- Particle Receiver System
- On-Sun Testing
- Conclusions and Next Steps

Prototype System Design

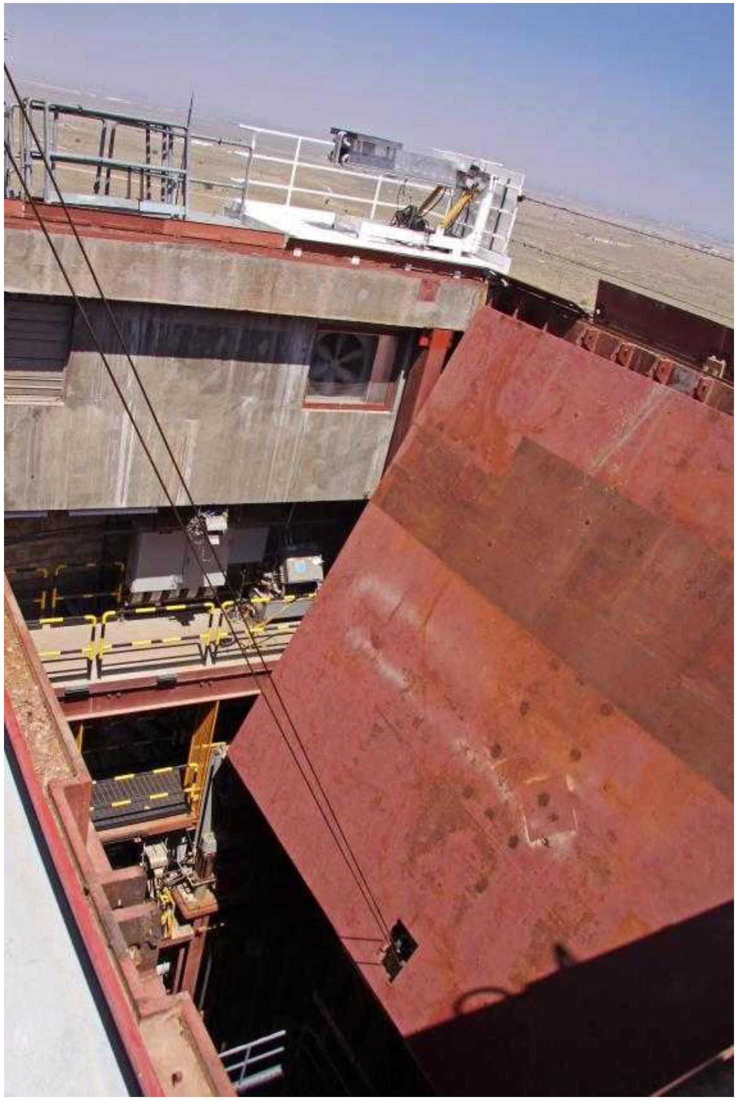


Staggered Chevron Array Receiver



Lifting the system to the top of the tower – June 22, 2015

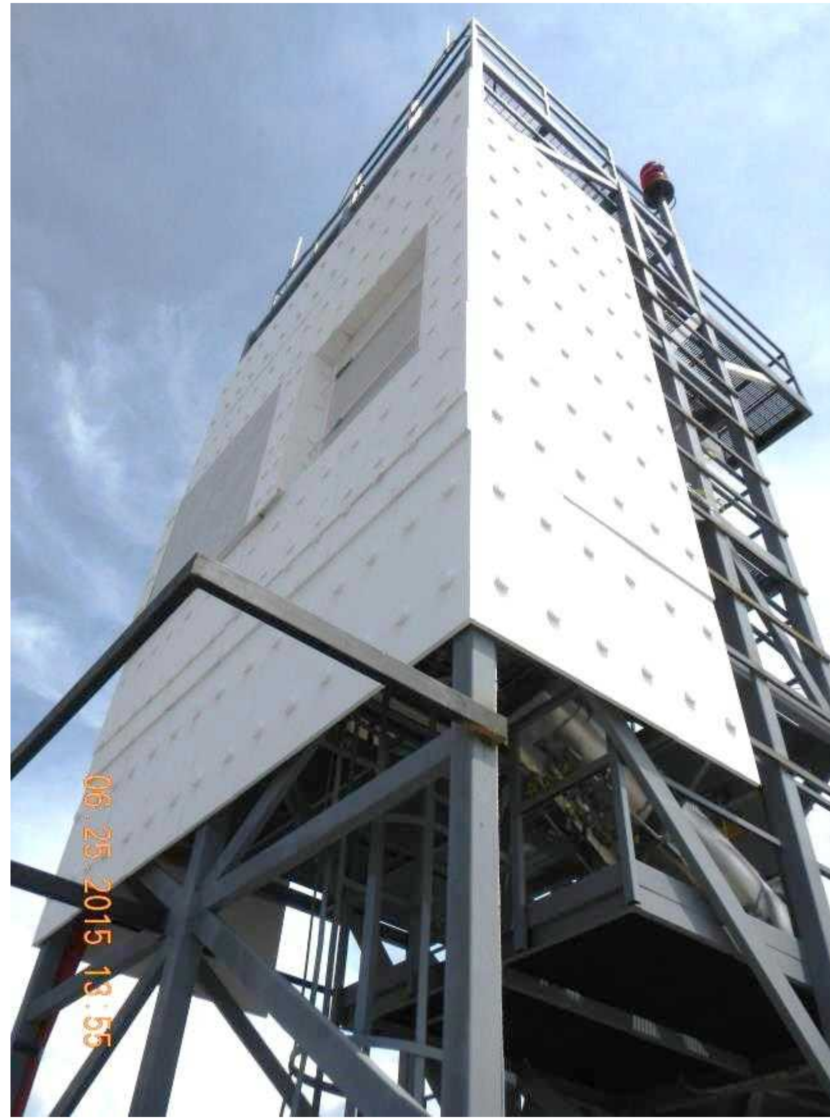
Lifting the system to the top of the tower



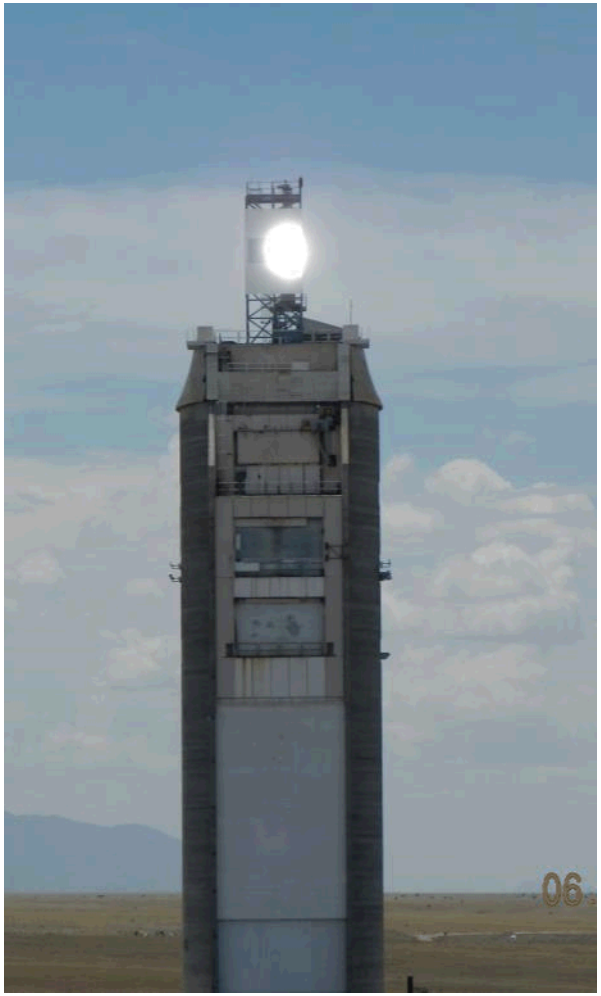
Lifting the system to the top of the tower

On-Sun Tower Testing

Sandia National Laboratories



On-Sun Tower Testing



Over 300 suns on receiver
(June 25, 2015)

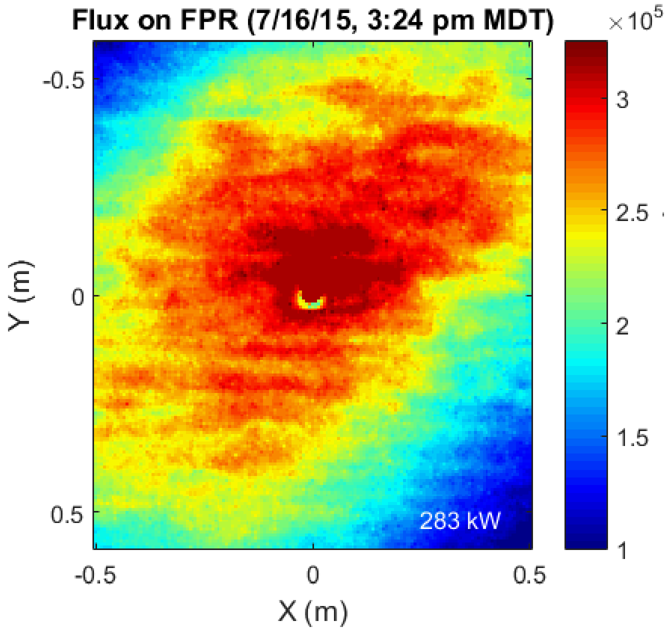
On-Sun Tower Testing

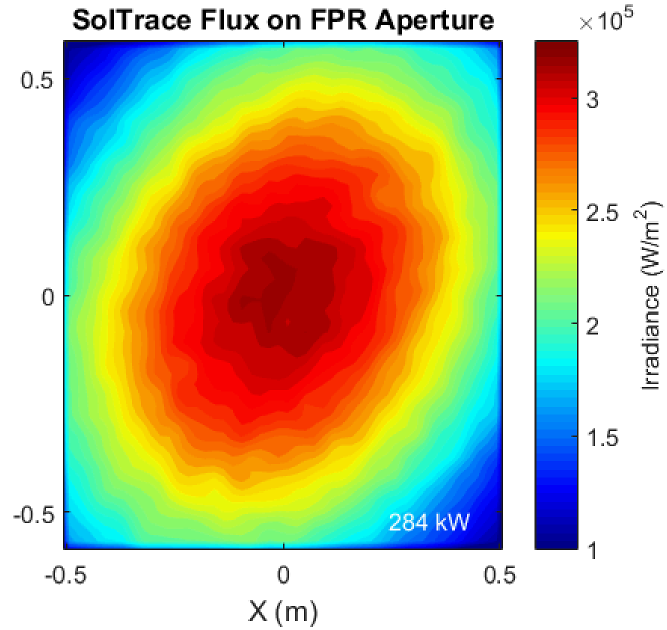
Over 600 suns peak flux on receiver
(July 20, 2015)

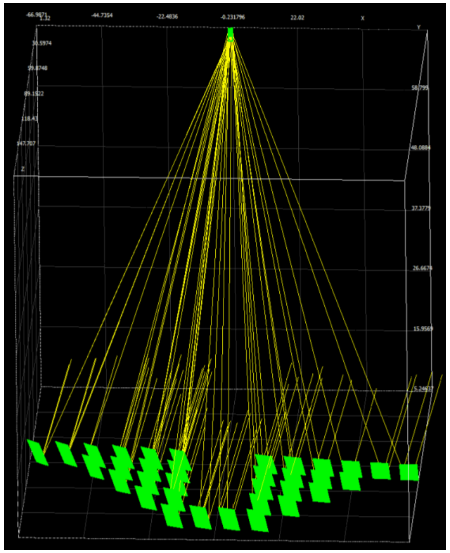
On-Sun Tower Testing

Particle Flow Through Mesh Structures
(June 25, 2015)

Irradiance Measurements



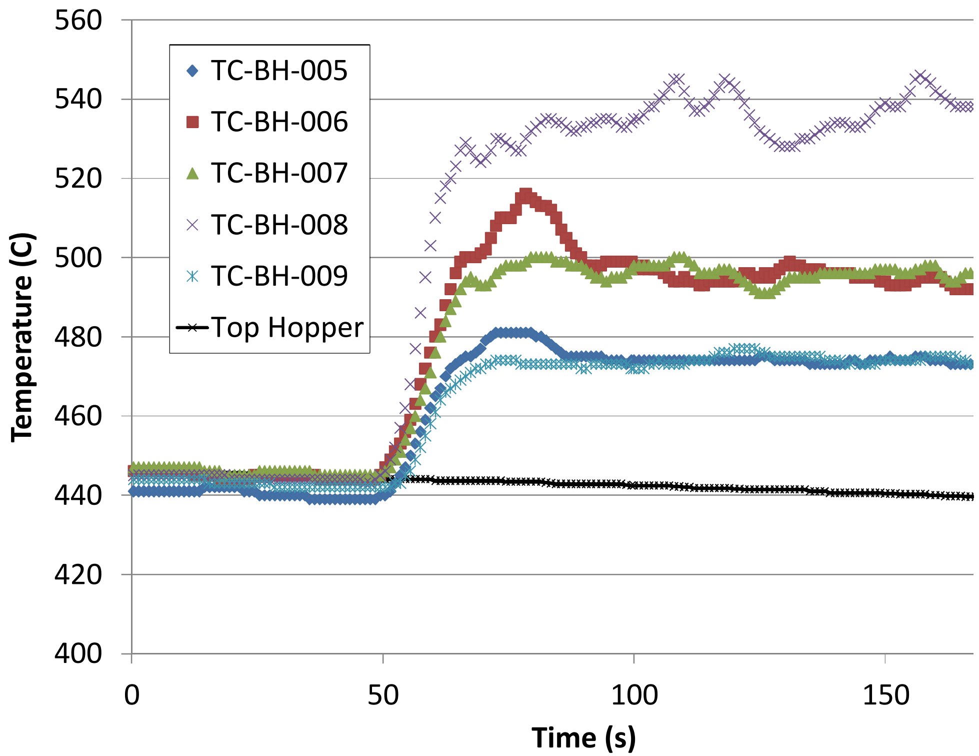


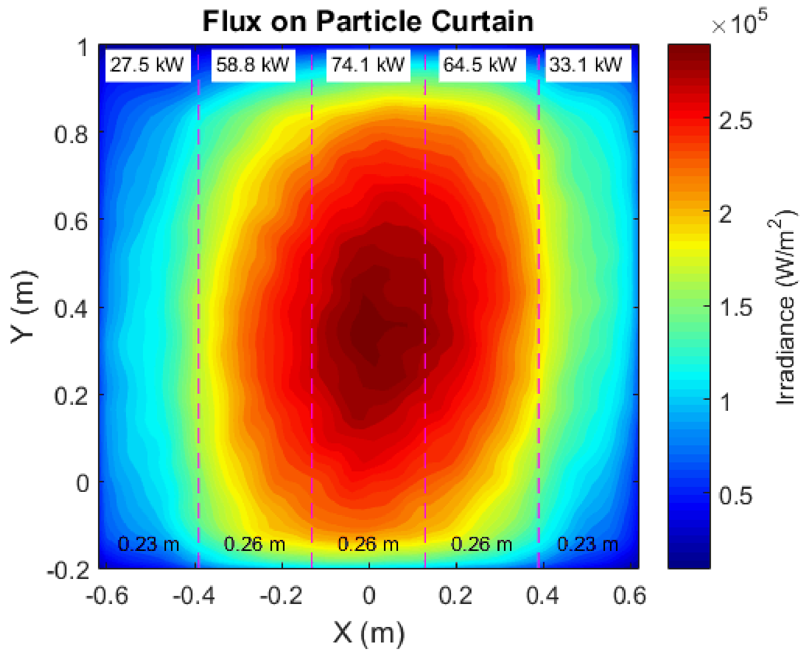


Measured

Simulated using Ray Tracing (SolTrace)

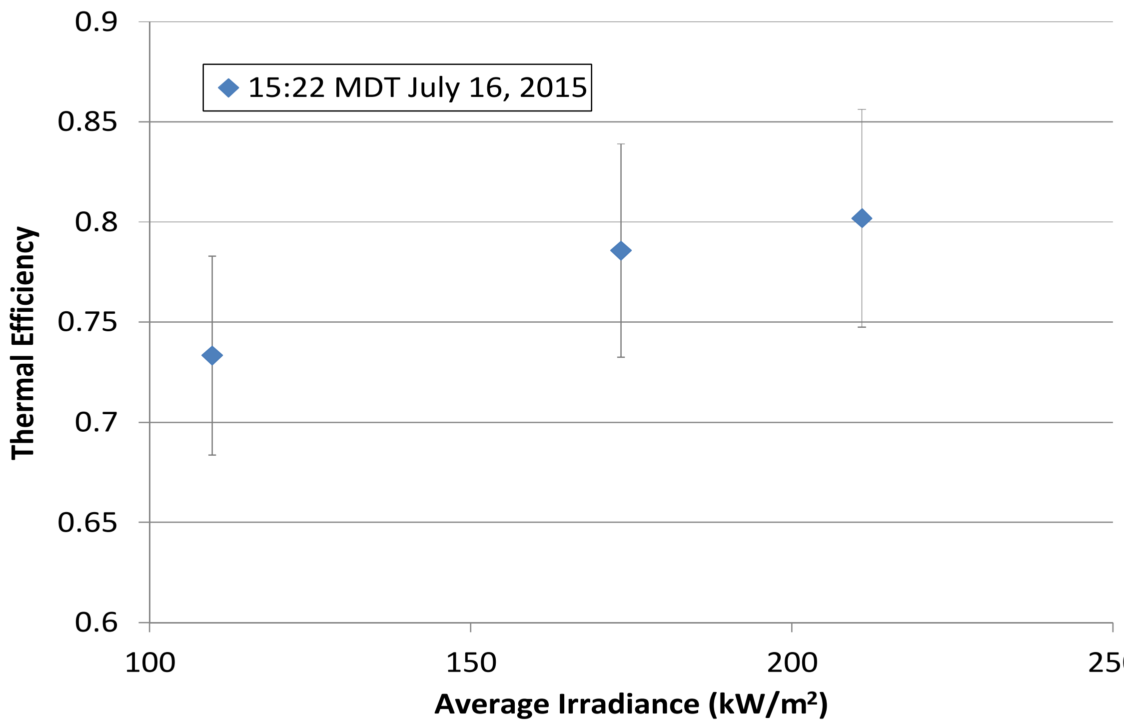
Temperature Measurements





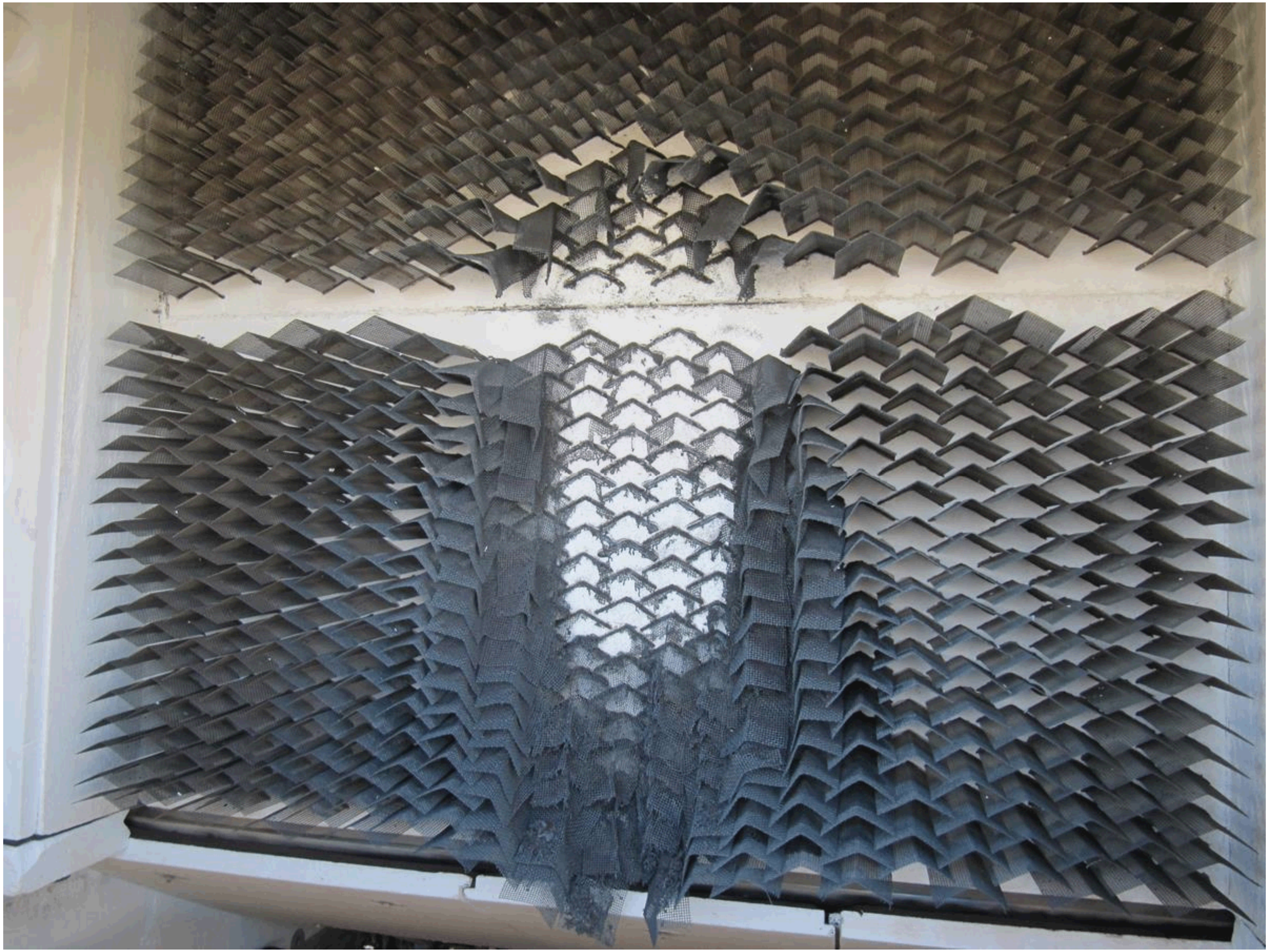
Summary of Results

Location	Average Irradiance (kW/m^2)	Average Particle DT per drop length (°C/m)	Average Particle Temperature (°C)	Specific Heat (J/kg-K)	Mass Flow Rate (kg/s)	Power absorbed by particles (kW)	Incident Power (kW)	Thermal Efficiency	Propagated % Relative Error in Efficiency
Outer two zones	110	27.4	457	1100	1.23	44.4	60.6	0.733	4.97
All zones	173	46.1	469	1100	3.32	203	258	0.786	5.33
Inner three zones	211	57.1	475	1110	2.09	158	197	0.802	5.44



Receiver Mesh Structures

July 24, 2015 – Nearly 700 suns



Overview

- Introduction and Objectives
- Particle Receiver System
- On-Sun Testing
- Conclusions and Next Steps

Conclusions

- Designed and constructed first continuously recirculating high-temperature particle receiver
  - Achieved peak particle temperatures over 800 C
  - Non-uniform irradiance caused non-uniform heating of particles
  - Average particle temperature rise per unit drop length was ~30 ˚C/m and ~60 ˚C/m at average particle irradiances of 100 and 200 kW/m^2, respectively
  - Thermal efficiency at particle inlet temperatures of ~440 ˚C ranged from ~70% to 80% at average particle irradiances of ~100 and 200 kW/m^2, respectively.

Next Steps

- Perform on-sun tests of free-falling particle curtain
- Received new DOE awards (FY16 – FY18)
  - Particle/sCO2 heat exchanger
  - Novel particle curtain designs

Acknowledgments

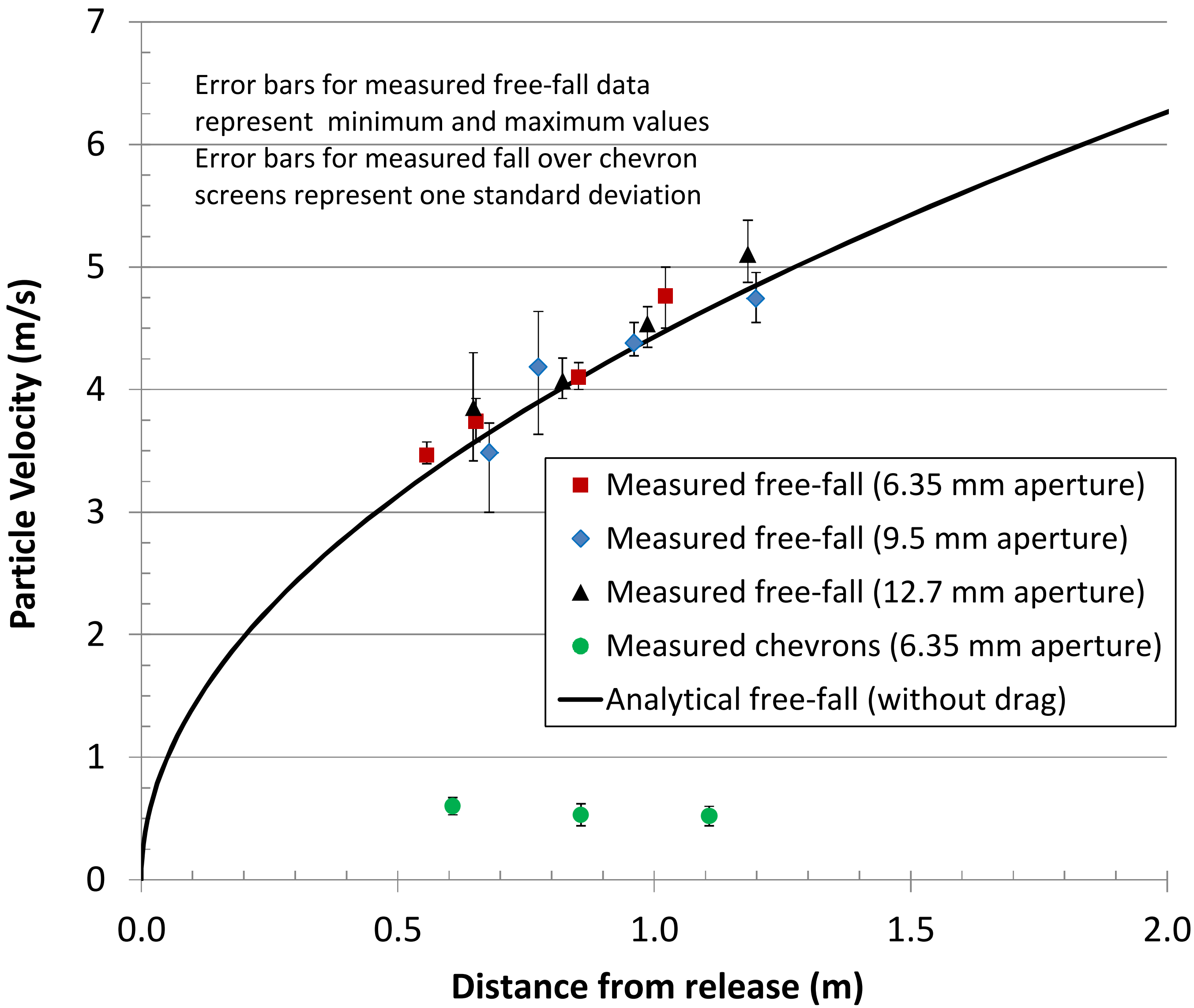
SunShot U.S. Department of Energy

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

Particle Velocities – Free fall vs. Obstructed



Ho, C.K., J. Christian, D. Romano, J. Yellowhair, and N. Siegel, 2015, *Characterization of Particle Flow in a Free-Falling Solar Particle Receiver*, in *Proceedings of the ASME 2015 Power and Energy Conversion Conference*, San Diego, CA, June 28 - July 2, 2015.

Sintering Potential

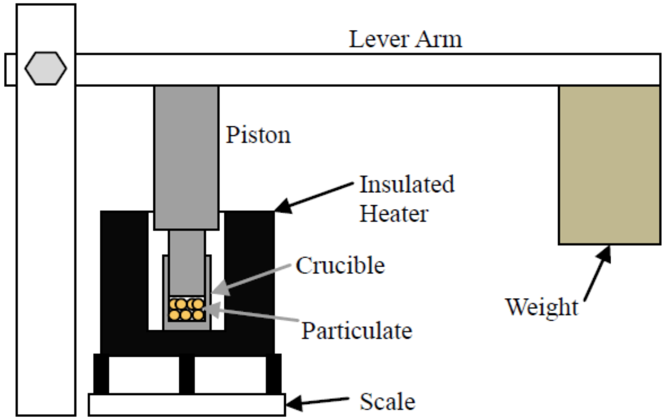


Figure 2. Diagram of Experimental Setup

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

Design of Experiments

- Factors
  - Particle size
  - Particle mass flow rate
  - Particle release location
  - Air curtain blower speed
  - External wind
- Metrics
  - Particle loss
  - Particle curtain spread

Impact of Air Curtain on Convective Heat Loss

- The air curtain generally increased convective losses in the system by ~0.5-1% for low initial particle temperatures of 25 C
- When the simulated initial particle temperature was increased to 600 C, the convective losses were reduced by 3.5 percentage