SunShot
U.S. Department of Energy

CSP Program Summit 2016

HIGH-TEMPERATURE FALLING PARTICLE RECEIVER

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energy.gov/sunshot

SAND2016-3641 PE

Overview

- Introduction
- Particle Receiver System
- On-Sun Testing
- Conclusions

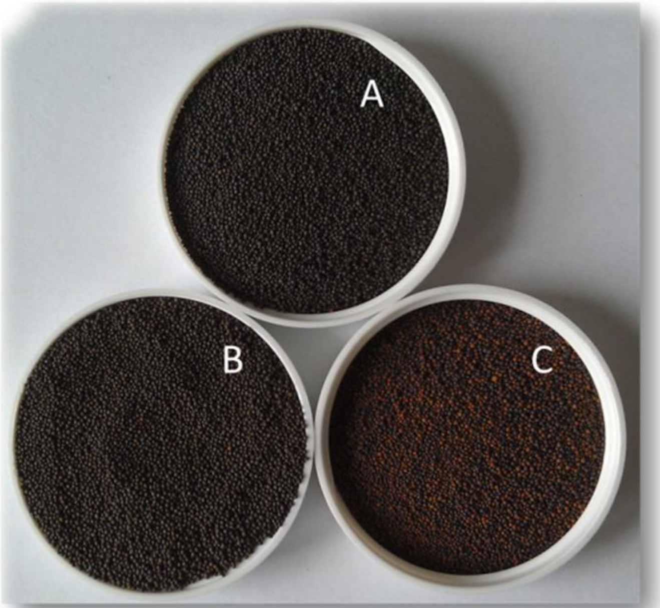
Motivation

- 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

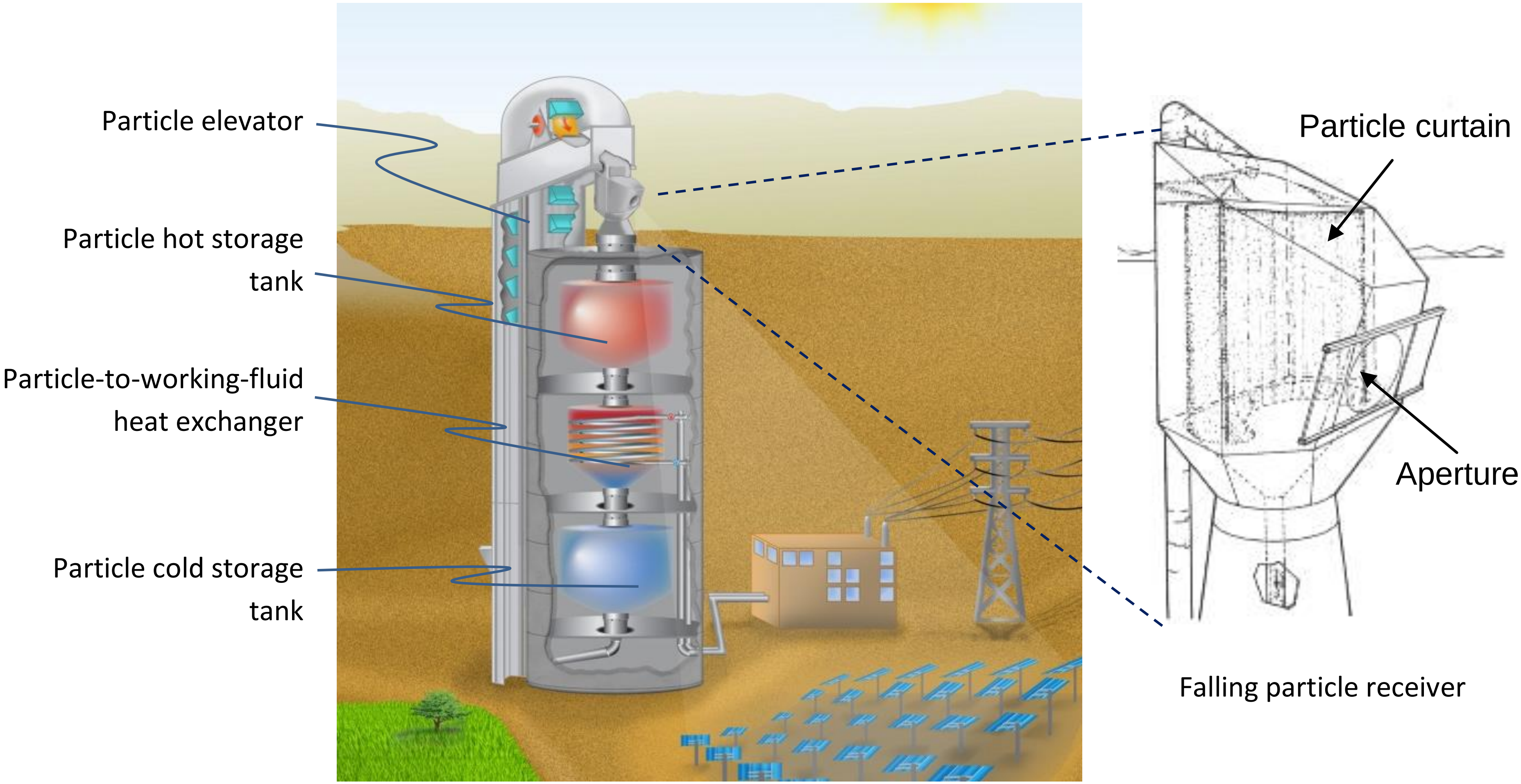
Advantages of Particle Receivers

- 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)



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

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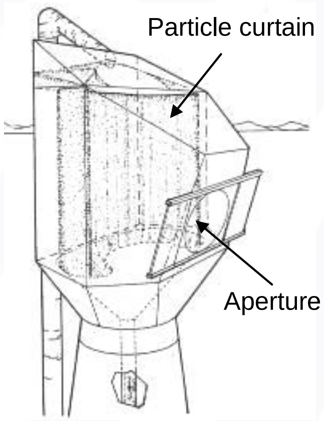
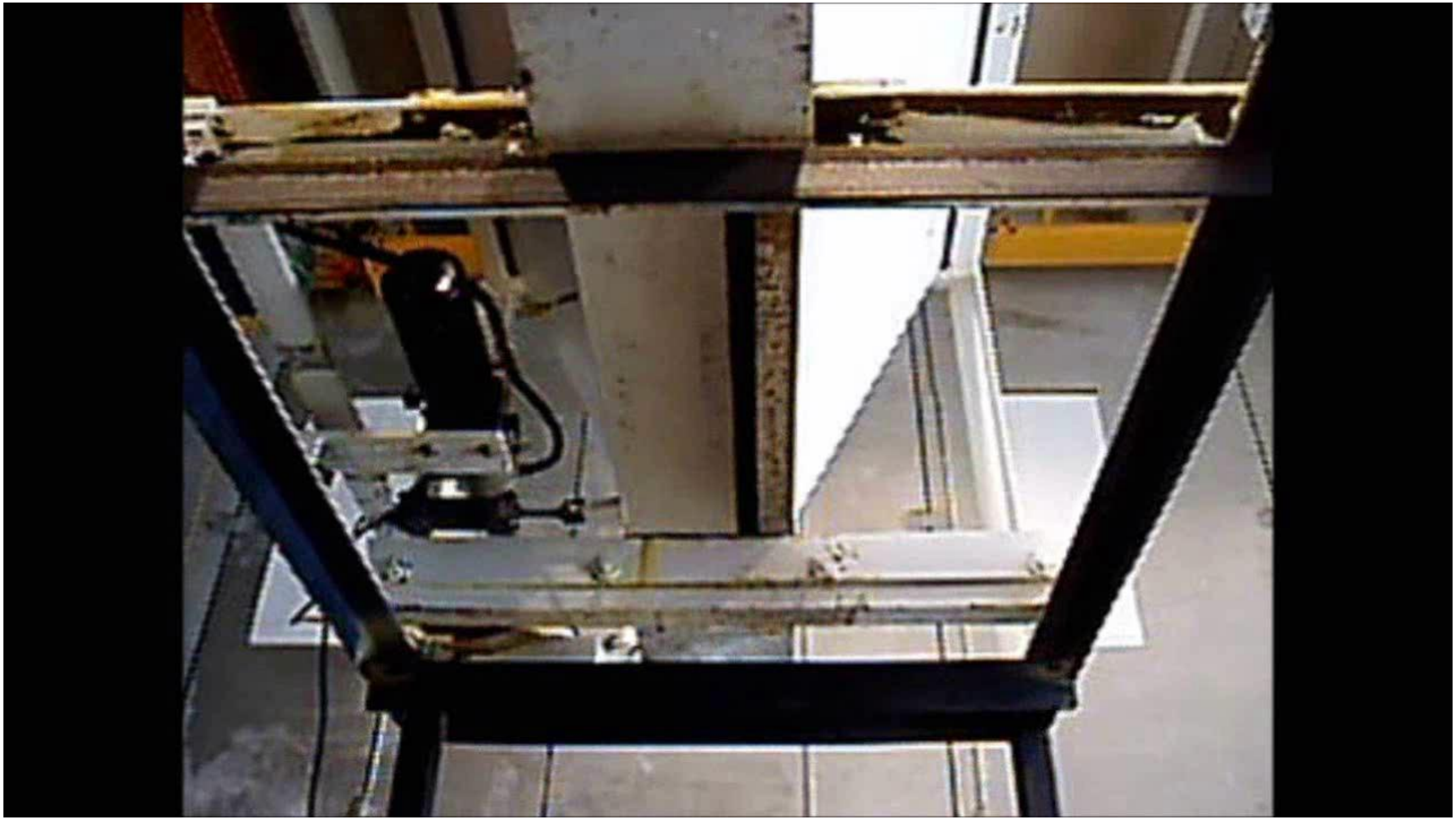
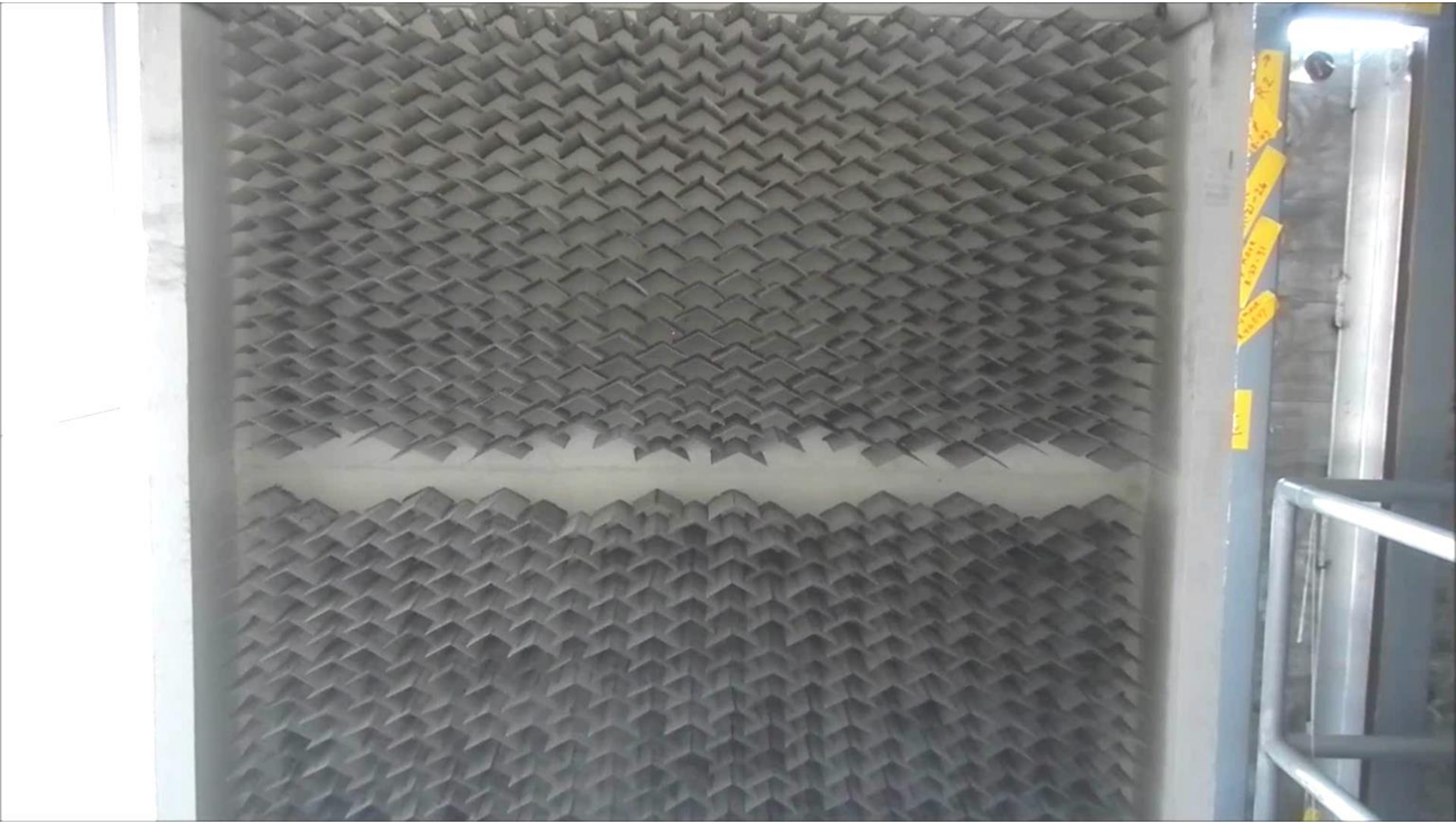
Receiver
Free-Fall vs. Obstructed Flow



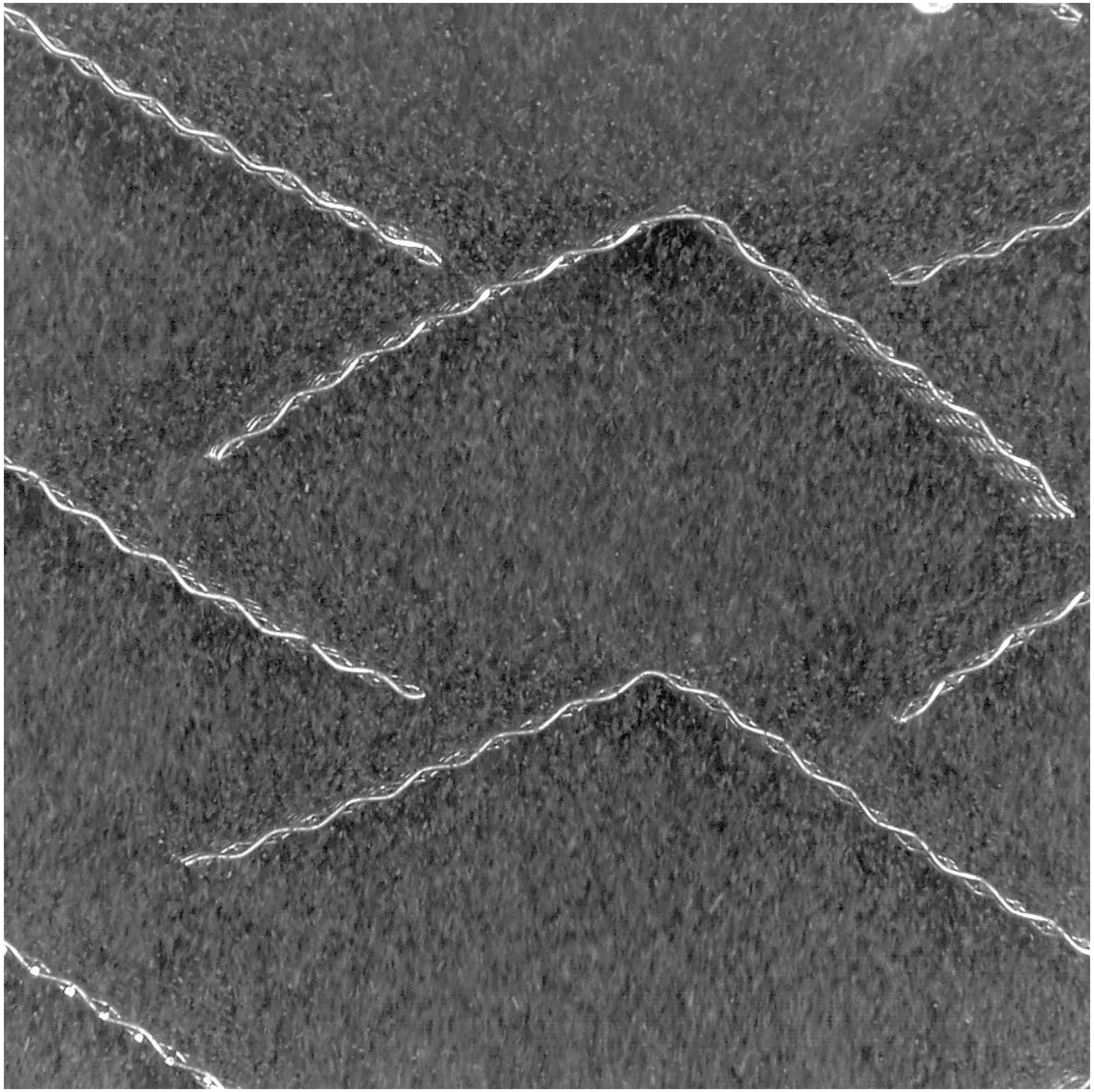
Particle Receiver Designs – Free Falling



Particle Receiver Designs – Pachinko



Particle Flow over Chevron Meshes



Pros: particle velocity reduced for increased residence time 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.

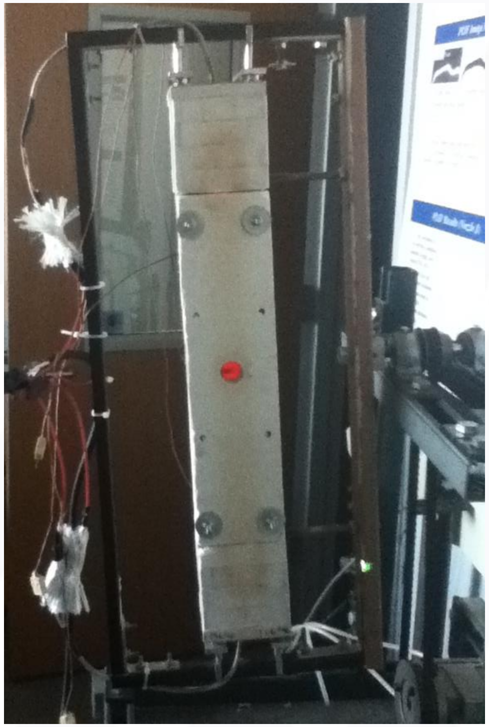
**Q is assumed to be 6x10^5 W/m^2 and T is assumed to be 700 °C (973 K): $\eta_{sel} = \frac{\alpha_s Q - \varepsilon\sigma T^4}{Q}$

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

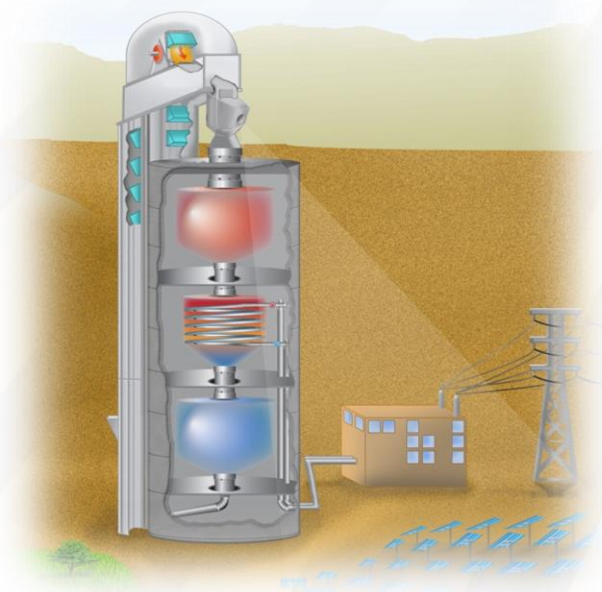
Ambient drop tests at ~10 m



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

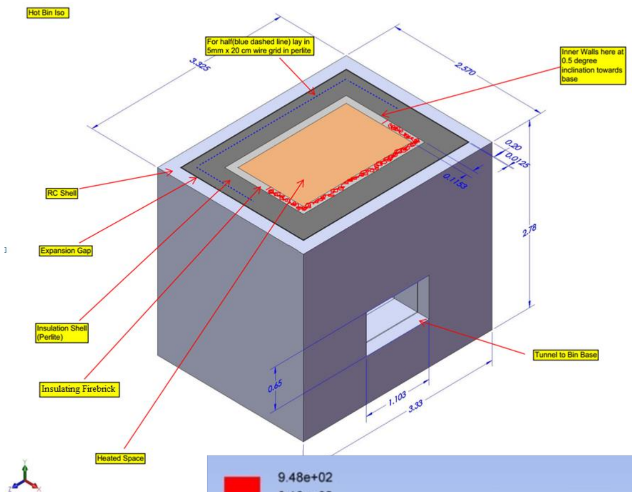
Knott, R., D.L. Sadowski, S.M. Jeter, S.I. Abdel-Khalik, H.A. Al-Ansary, and A. El-Leathy, 2014, *High Temperature Durability of Solid Particles for Use in Particle Heating Concentrator Solar Power Systems*, in *Proceedings of the ASME 2014 8th International Conference on Energy Sustainability*, ES-FuelCell2014-6586,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

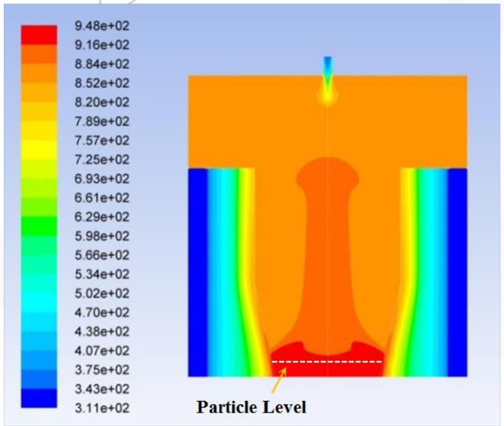
Balance of Plant



Thermal Storage

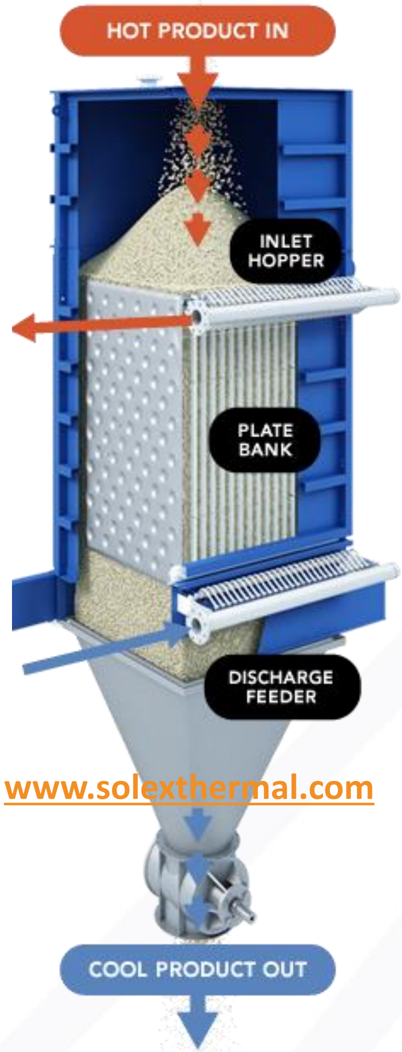
- Experimental evaluation and modeling of prototype thermal energy storage designs



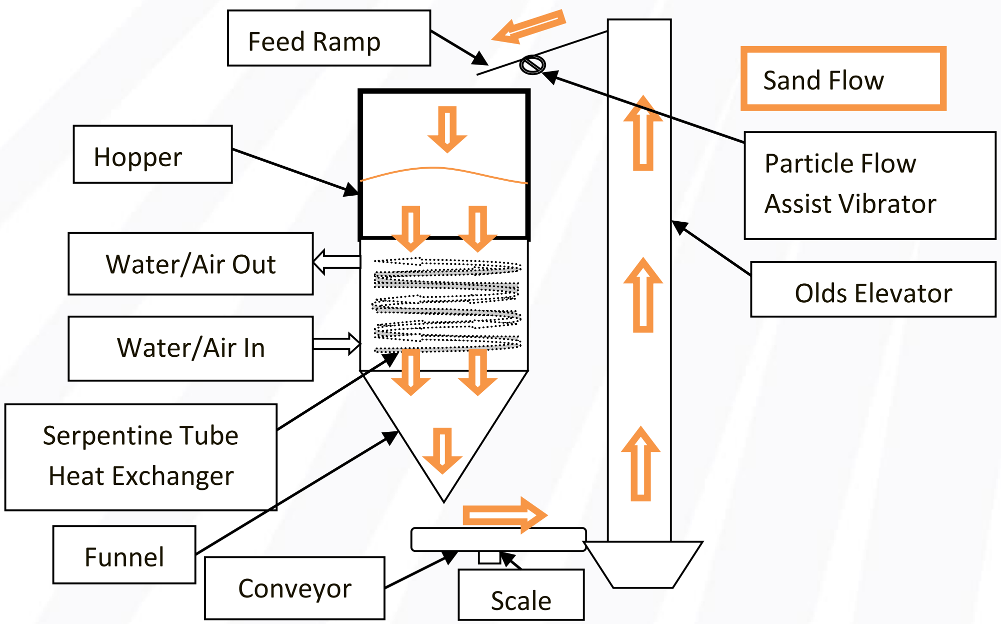


El-Leathy et al., "Experimental Study of Heat Loss from a Thermal Energy Storage System for Use with a High-Temperature Falling Particle Receiver System," SolarPACES 2013

Particle to Working Fluid Heat Exchanger



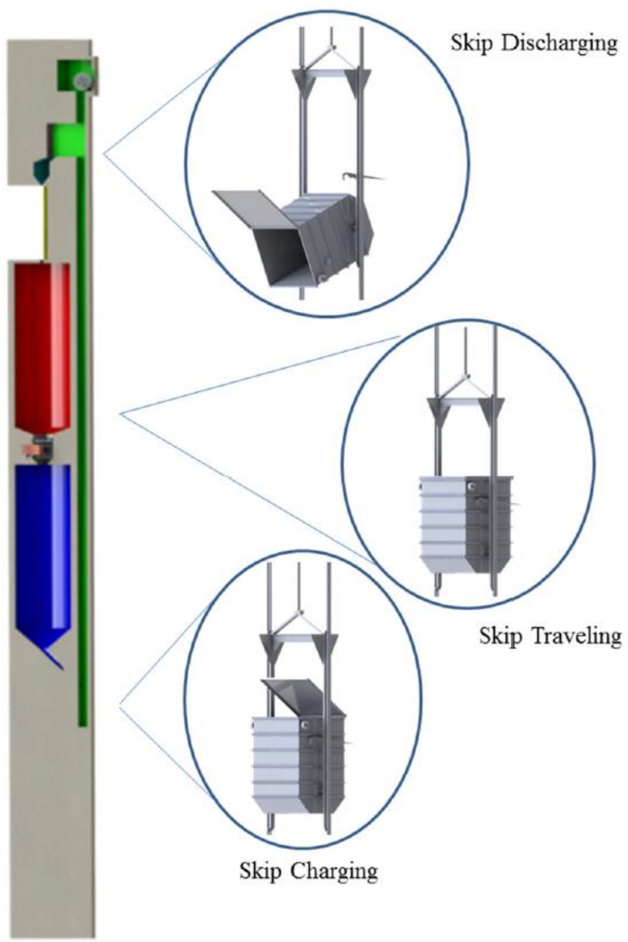
- Experimental evaluation of heat transfer coefficients & particle flow



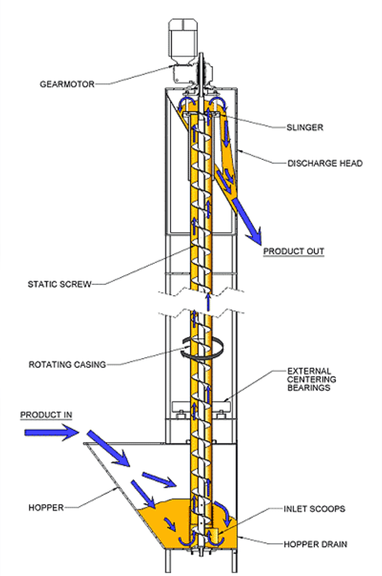
Golob et al., 2013, "Serpentine Particle-Flow Heat Exchanger with Working Fluid, for Solar Thermal Power Generation," SolarPACES 2013

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 ~ 500 °C
  - Different lift strategies evaluated
    - Screw-type (Olds elevator)
    - 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

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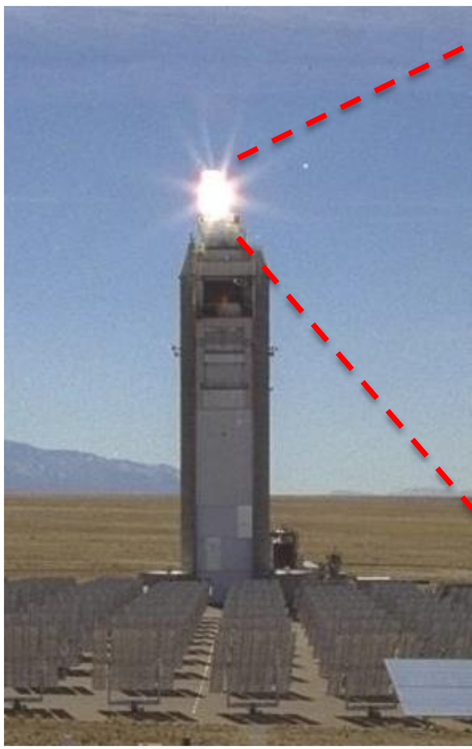
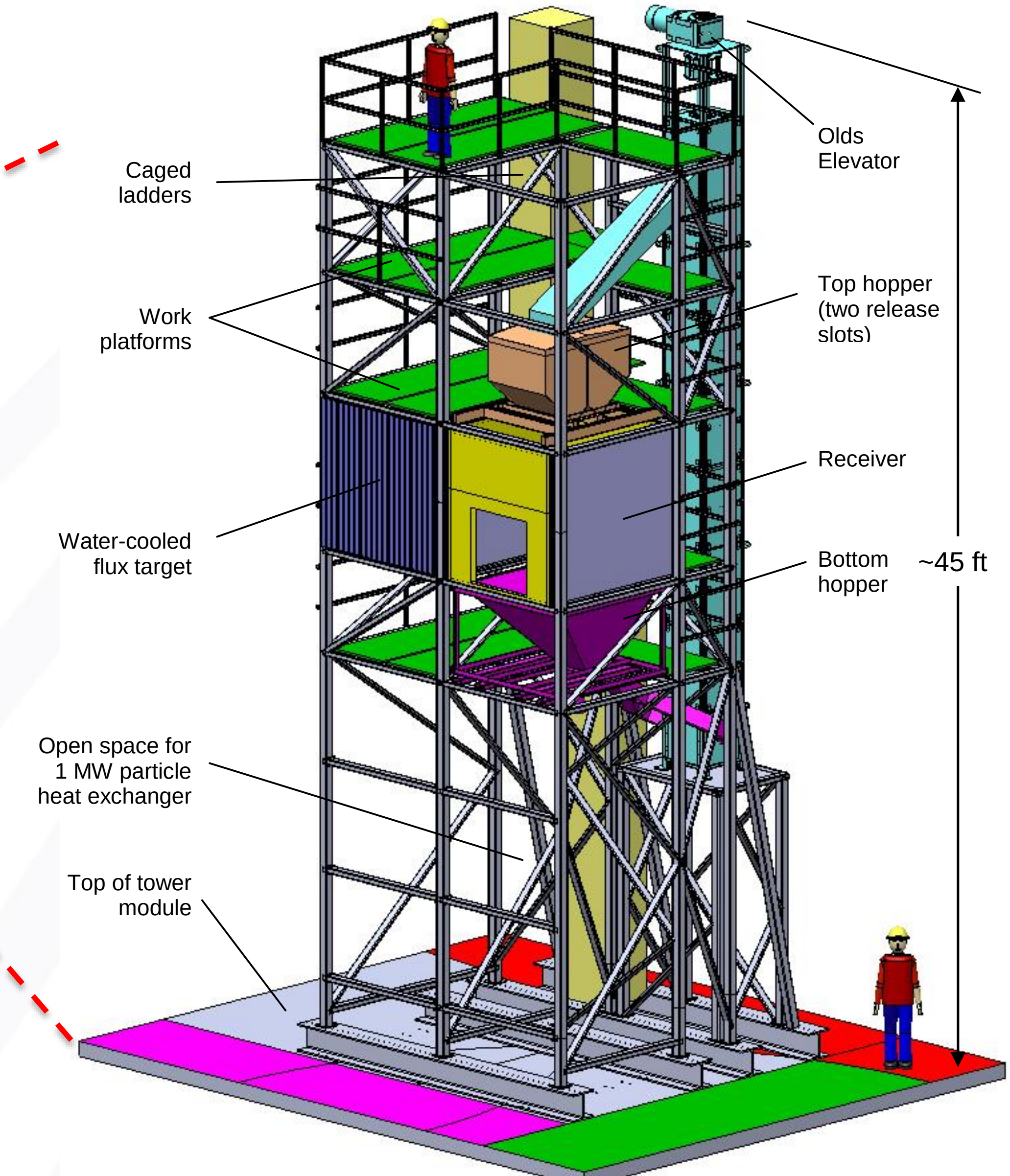
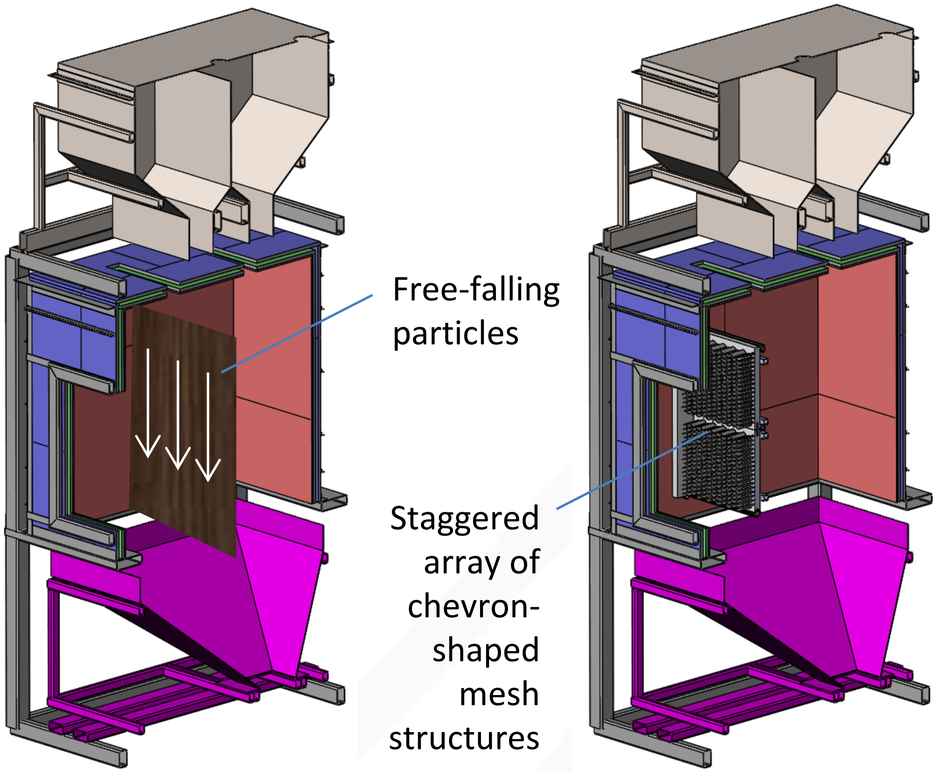
Prototype System Design



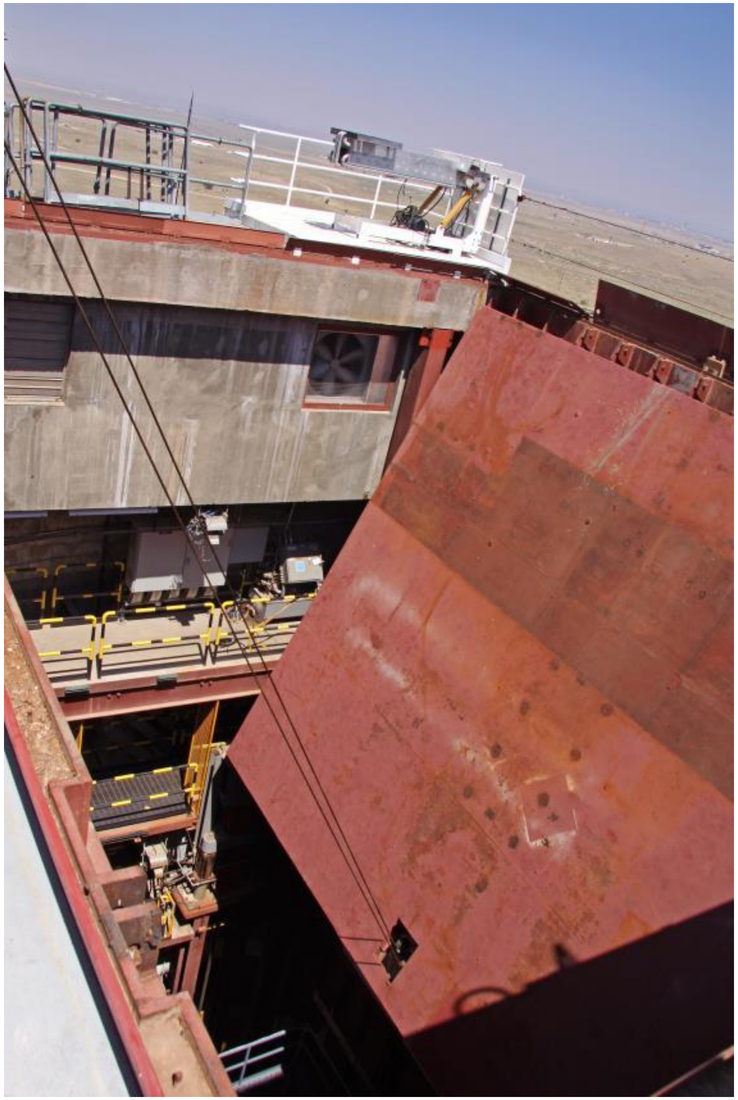


Particle Release Configurations



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

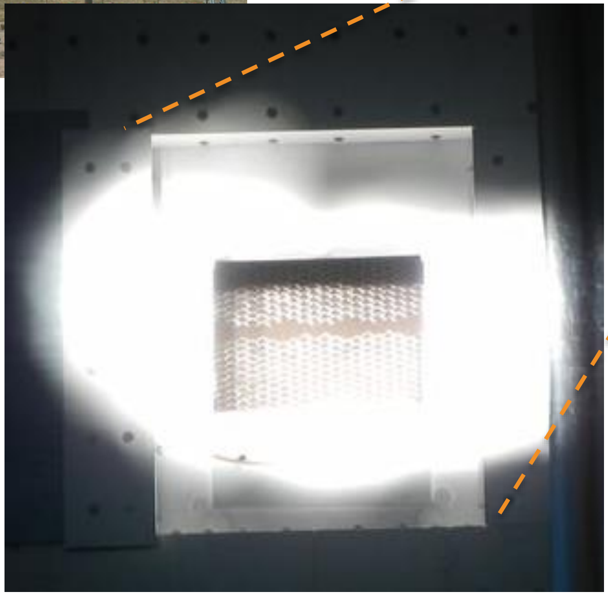
Lifting the system to the top of the tower

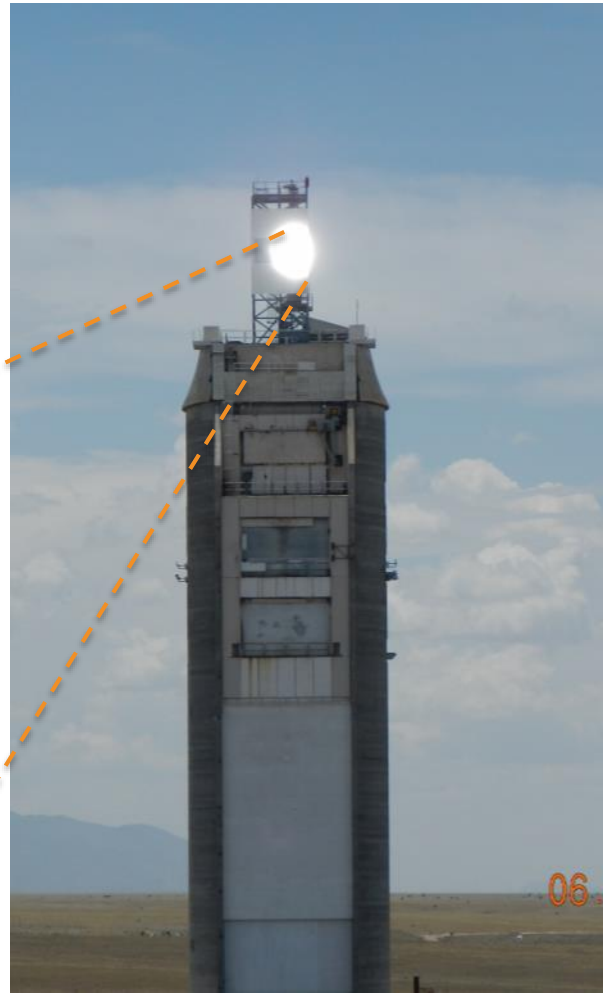


Lifting the system to the top of the tower

Prototype System on Tower

On-Sun Tower Testing



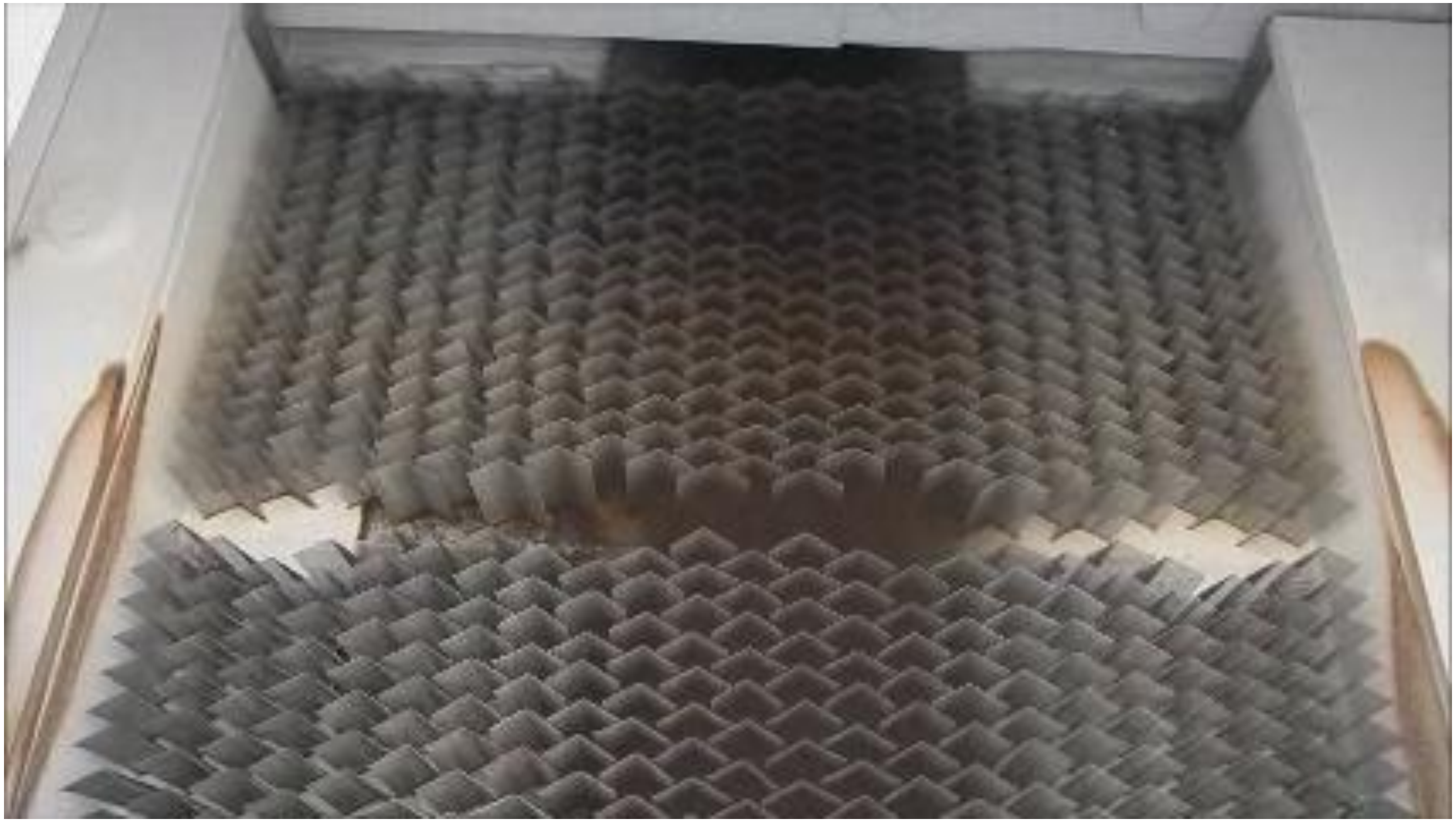


Over 300 suns on receiver
(June 25, 2015)

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)

Overview

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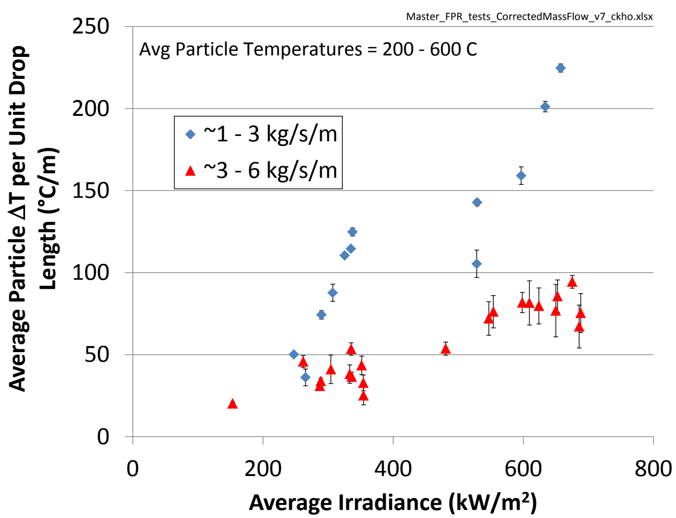
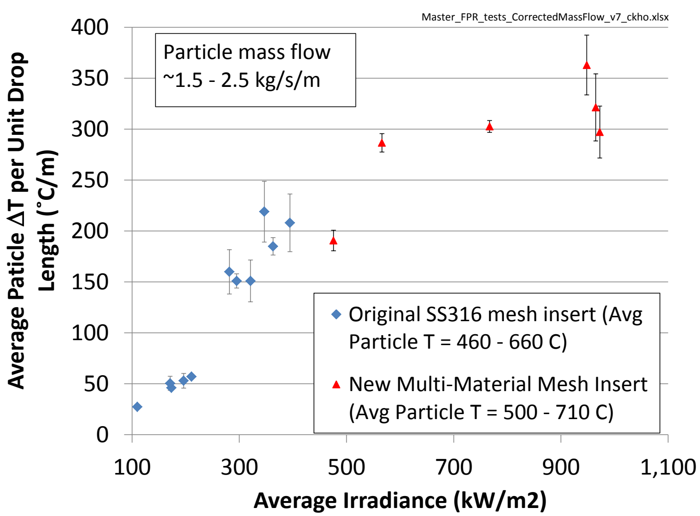
Conclusions

- Designed and constructed first continuously recirculating, on-sun, high-temperature particle receiver
  - Achieved average particle outlet temperatures >700 °C
    - Peak particle outlet temperatures >900 °C
  - Particle heating up to ~200 – 300 °C/(m of drop)
  - Thermal efficiency ~70% to 80%



Free-Fall



Obstructed-Flow

Next Steps

- Received new DOE awards (FY16 – FY18)
  - Particle/sCO2 heat exchanger
  - Novel particle curtain designs
- Improve receiver efficiency
  - Receiver geometry, shape, size, nod angle
  - Aperture coverings
- Reduce particle loss
  - Abrasion/wear
  - Wind
- System designs for scale-up (≥ 10 MW_e)

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
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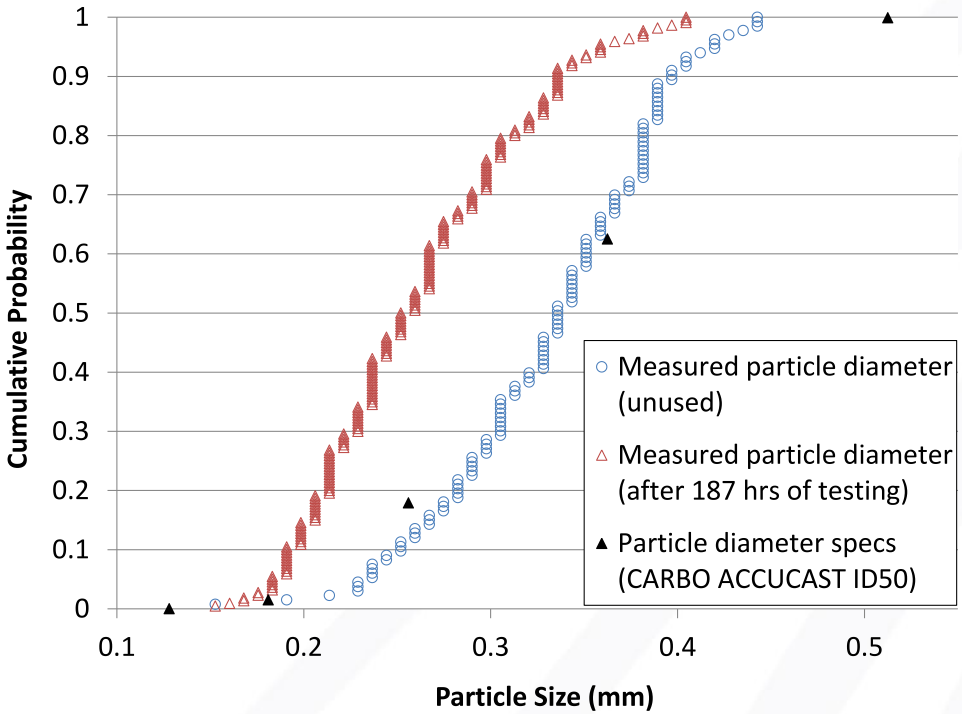
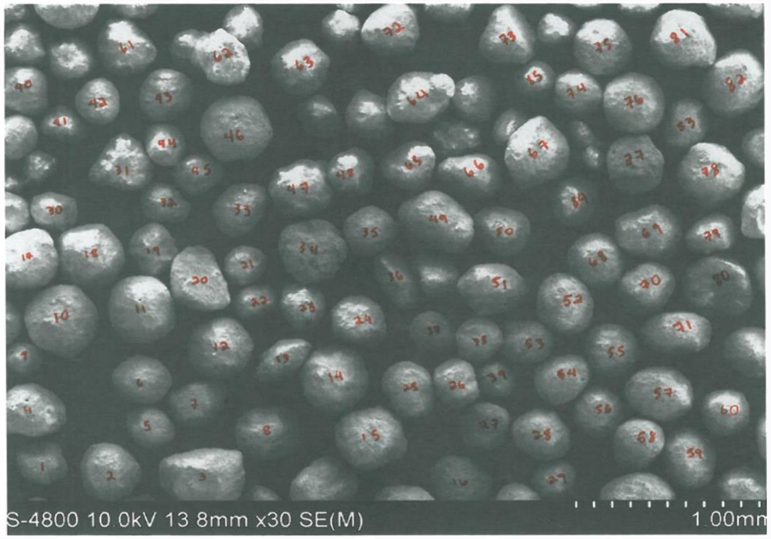
- **Bucknell University**
  - Nate Siegel, Michael Gross
- **King Saud University**
  - Hany Al-Ansary, Abdelrahman El-Leathy, Eldwin Djajadiwinata, Abdulaziz Alrished
- **DLR**
  - Birgit Gobereit, Lars Amsbeck, Reiner Buck

Backup Slides

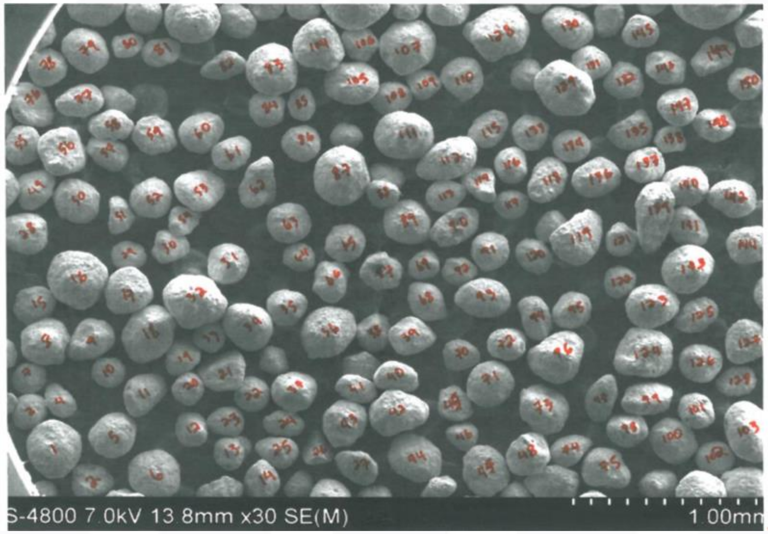
SEM Images of Used and Unused Particles



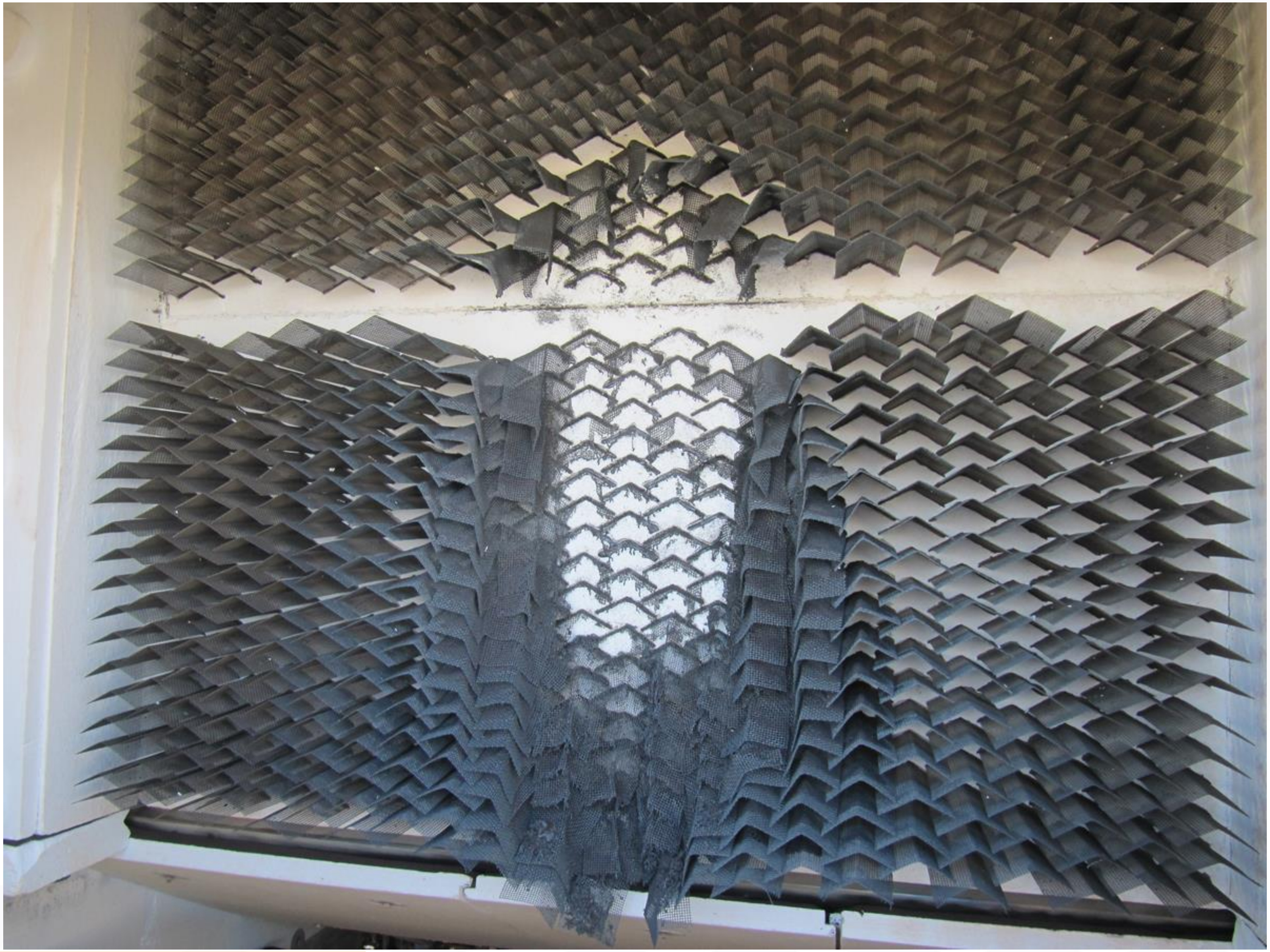
Unused



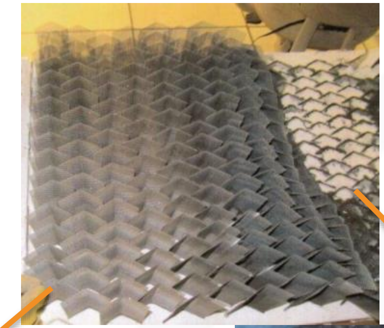
Used

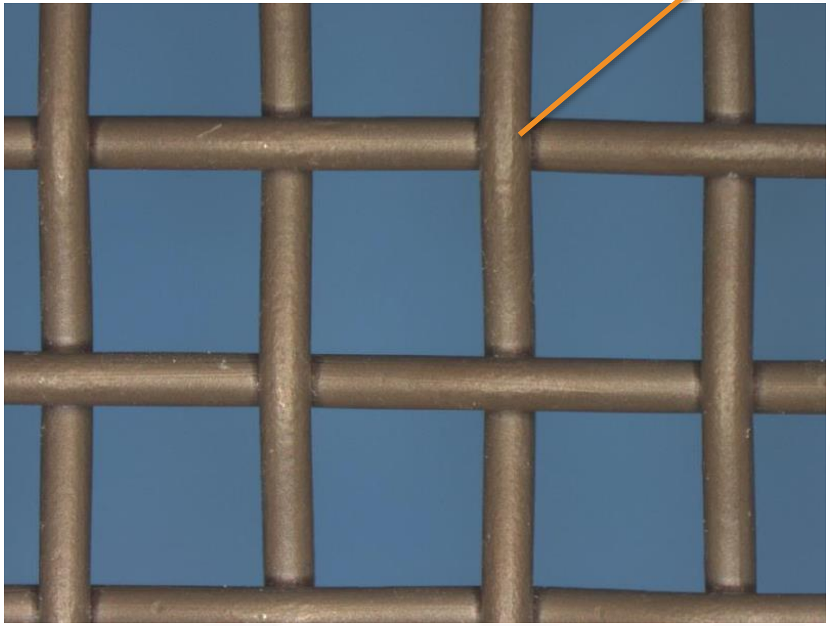


July 24, 2015 – Nearly 700 suns

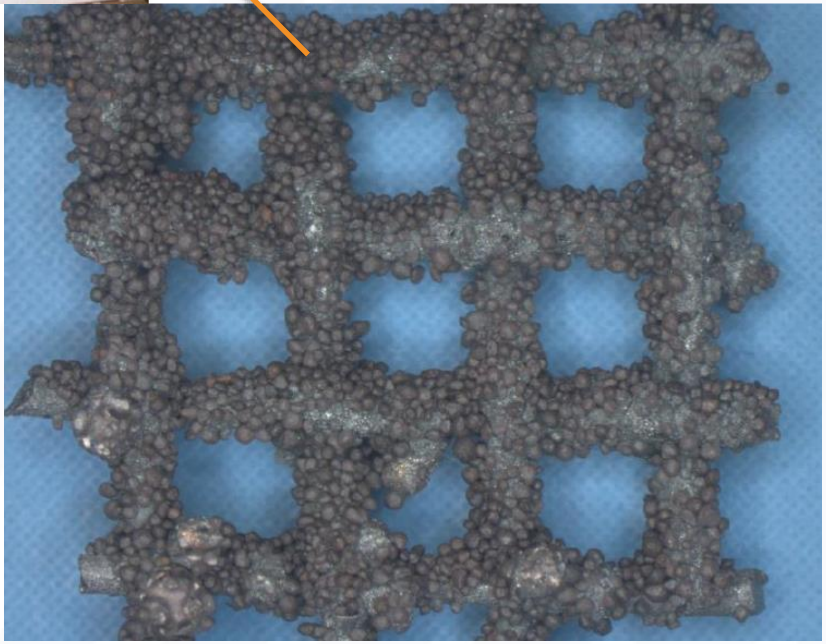


SS316 Mesh Failure Analysis



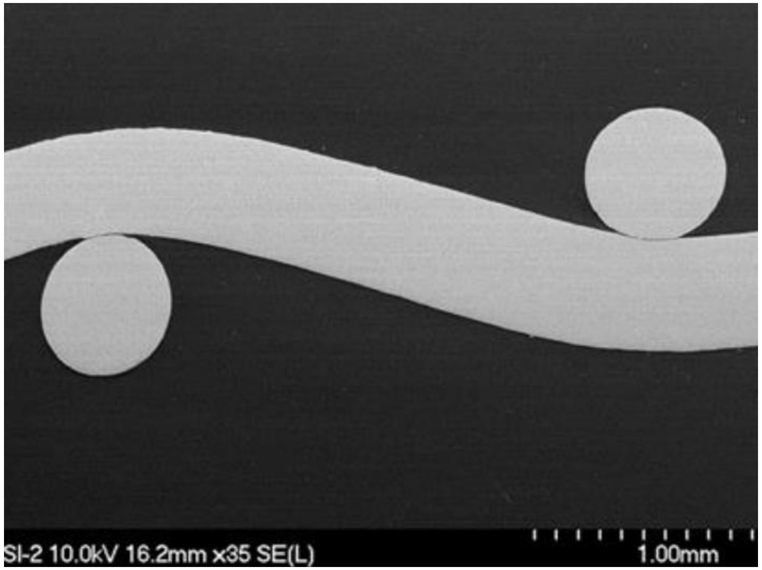


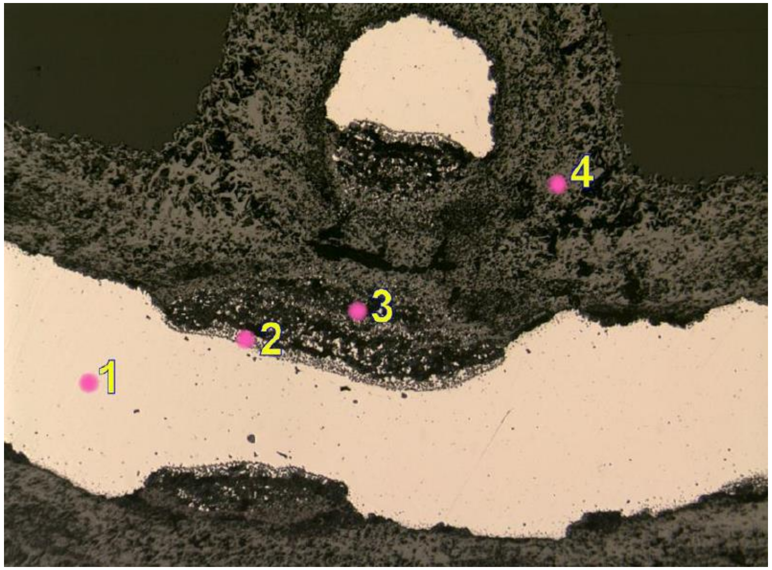
Mesh located far from failed region



Mesh located within failed region
(ceramic particles sintered on mesh)

SS316 Mesh Failure Analysis



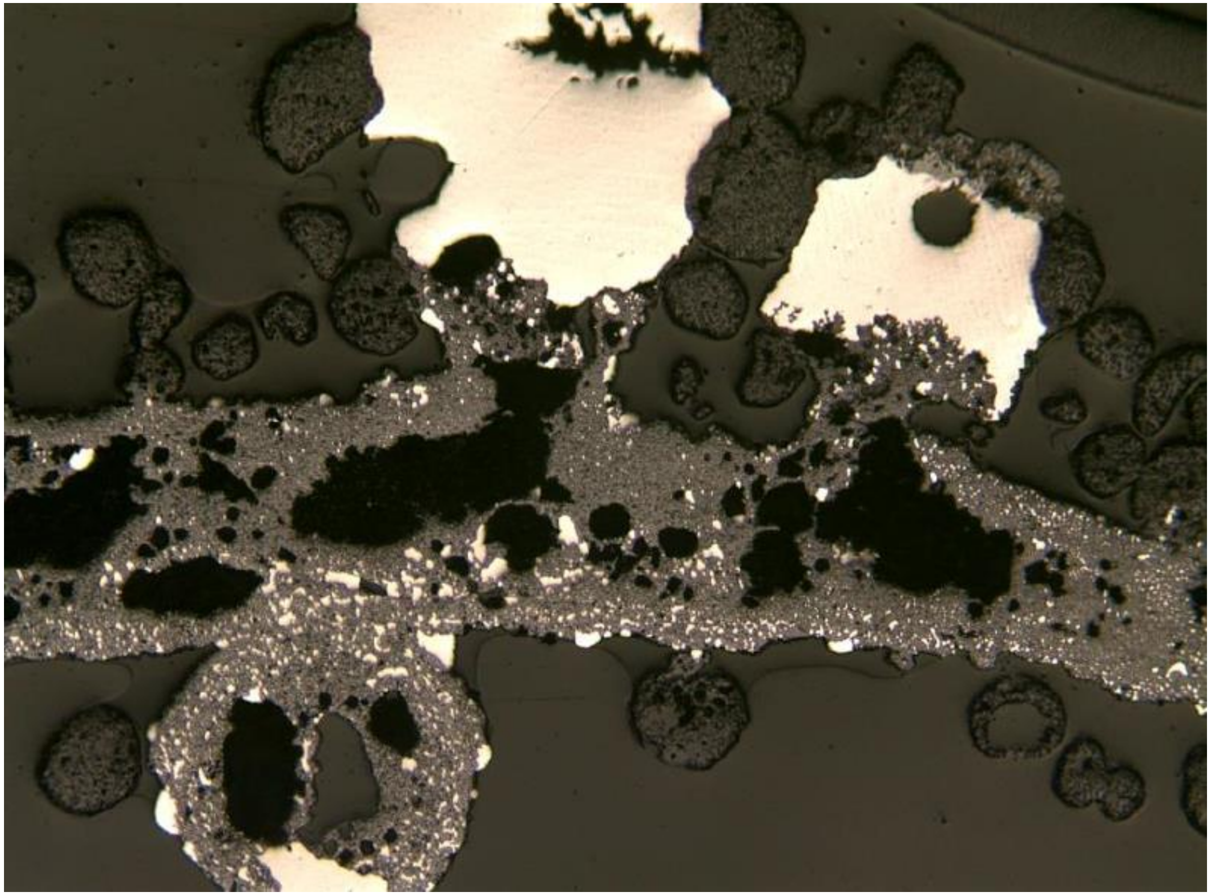


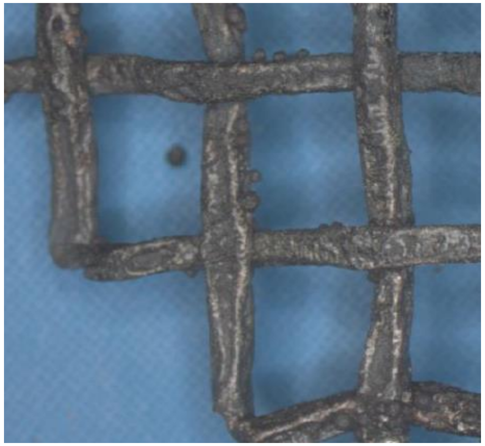
Top left: cross-sectional view of intact wire mesh

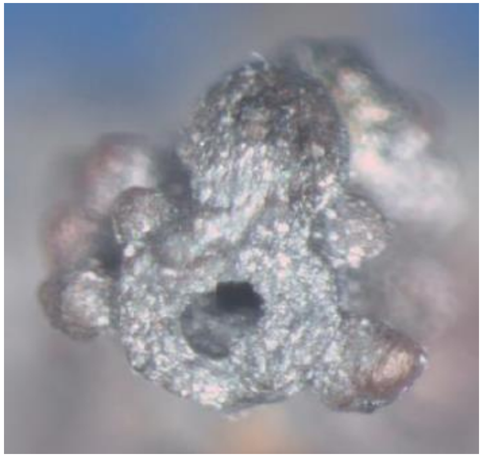
Top right: cross-sectional view of oxidized wire mesh

	Fe	Cr	Ni	Mo	O	Al	Si
	(Wt% EDS semi-quant, standardless EDS)						
Location 1 **Wire core**	67	20	6.7	5.2	-	-	-
Location 2 **"intermetallic layer"**	19	4.45	44	11	19	1.64	1.34
Location 3 **Oxidized zone**	22	18	4.39	5.26	48	1.1	1.75
Location 4 **Oxidized zone**	34	10	2.89	2.32	48	-	1.45

SS316 Mesh Failure Analysis

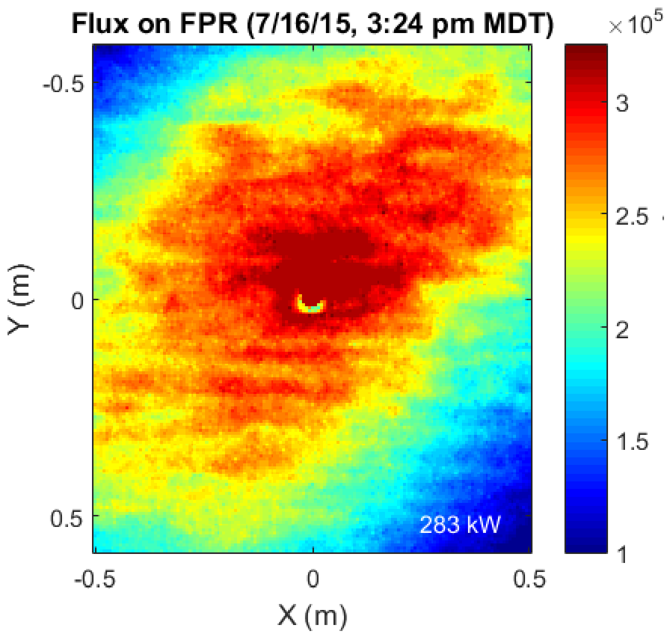


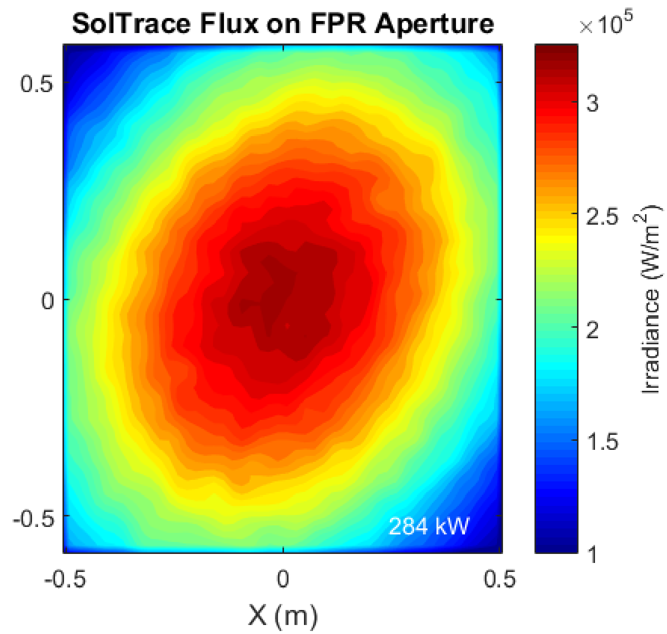


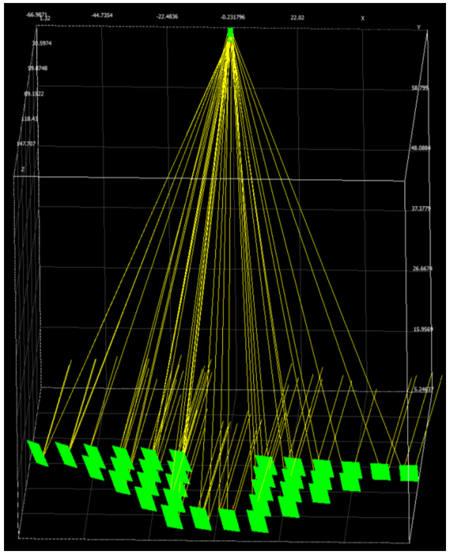


Cross-sectional view of oxidized wire mesh; wire ruptured and “leaked” molten steel out of oxidized shell (white is stainless steel, rough gray area is oxidized mesh)

Irradiance Measurements



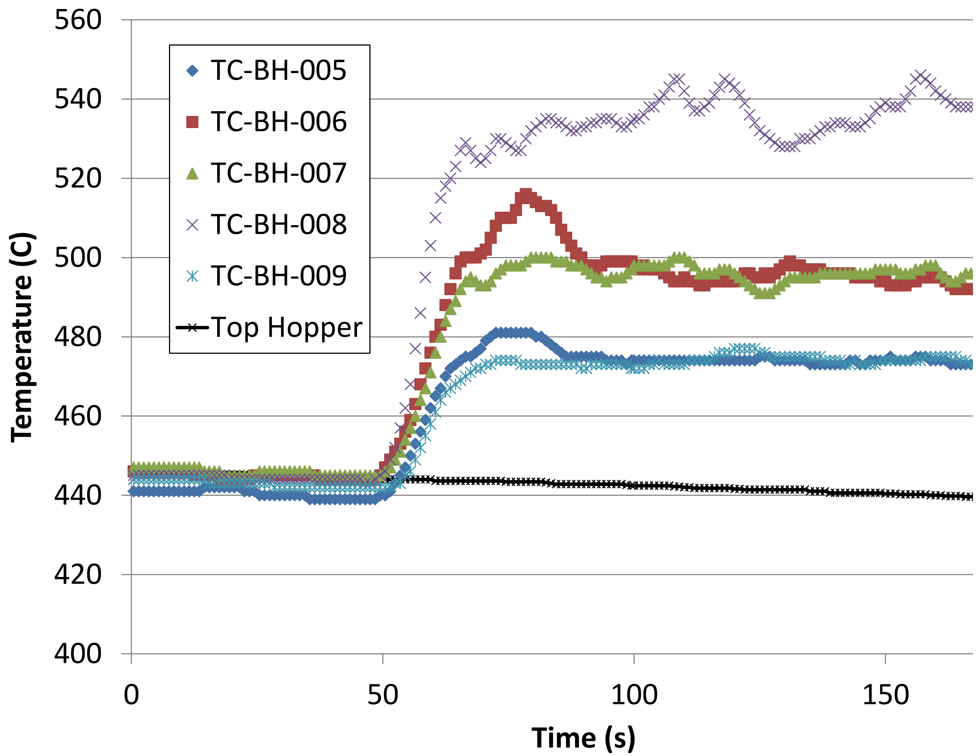


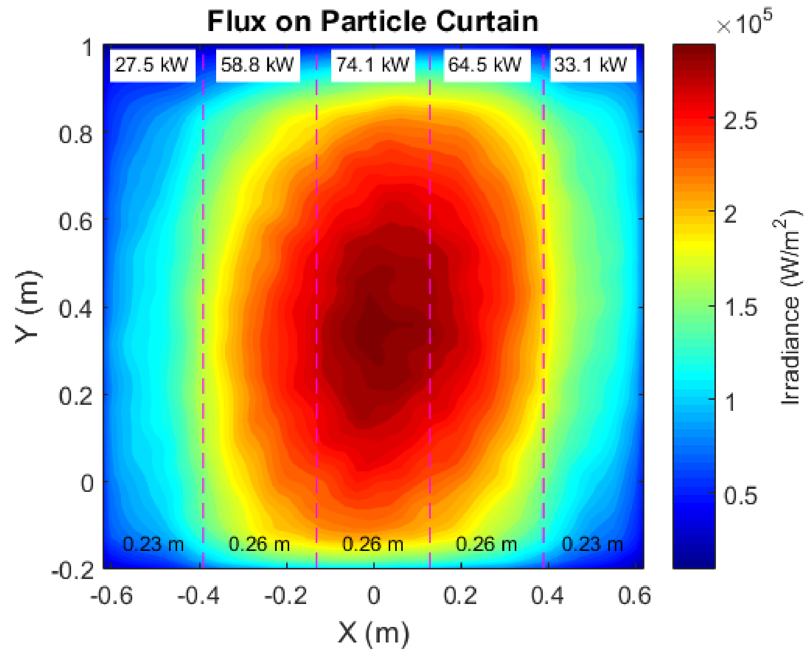


Measured

Simulated using Ray Tracing (SolTrace)

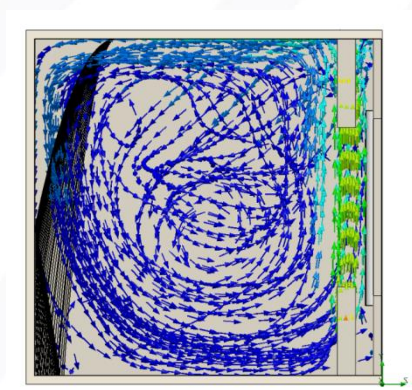
Temperature Measurements



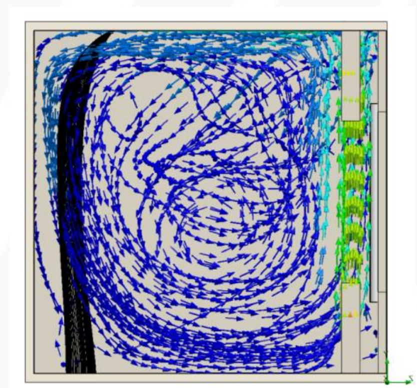


Air Curtain Modeling (SNL)

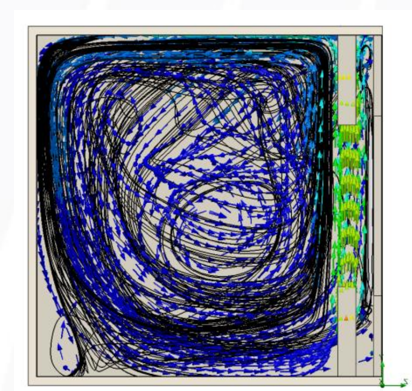
- Evaluate use of air recirculation along aperture to reduce heat loss and impacts of external wind
  - Investigate particle size, location, particle flow rate, air flow rate, external wind



1 mm particle size



100 μm particle size



10 μm particle size