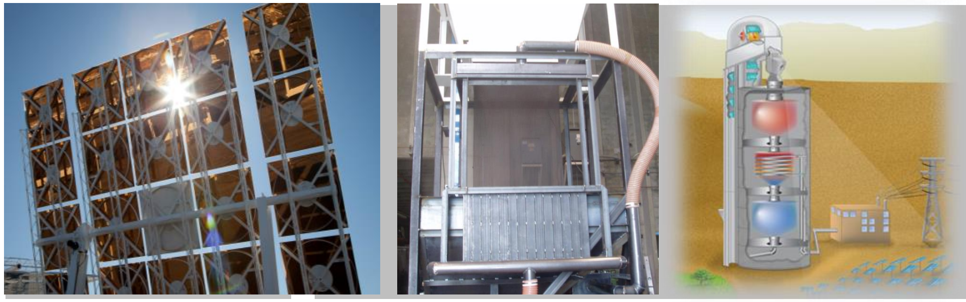
High-Temperature Falling Particle Receiver for Concentrating Solar Power

SAND2016-5660PE

Exceptional service in the national interest

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



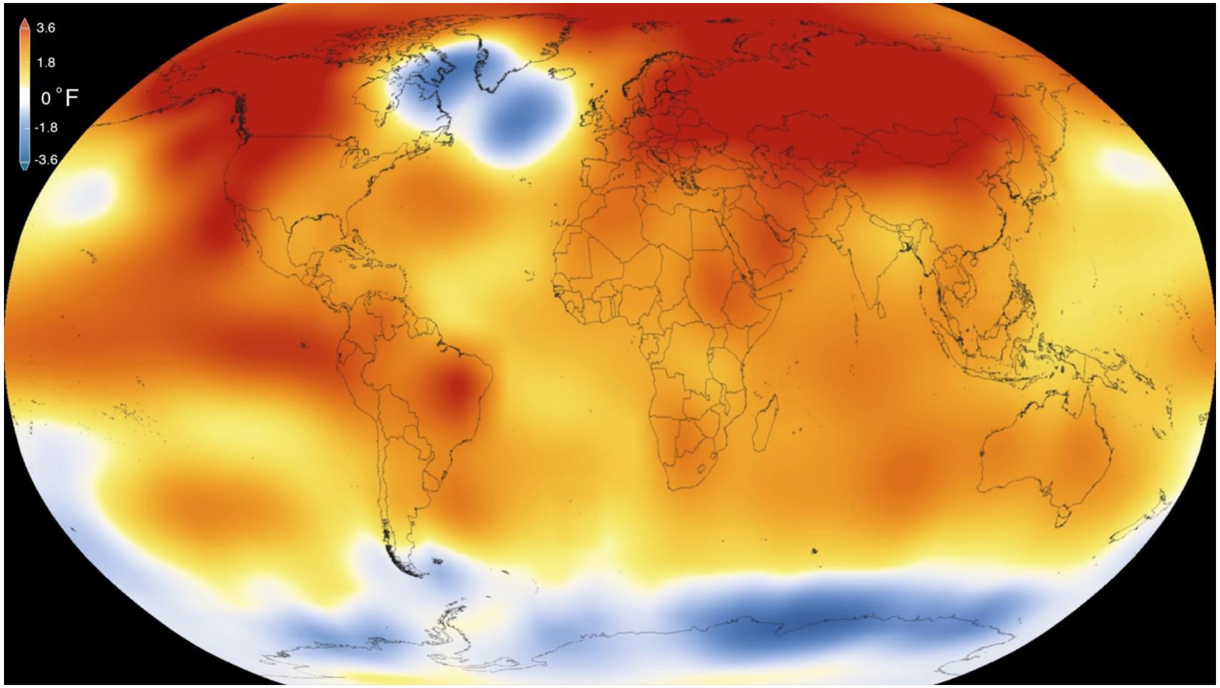
Clifford K. Ho, Principal Investigator
Sandia National Laboratories
Concentrating Solar Technologies Dept.

Overview

- Why do we need it?
- How does it work?
- What is the impact?

Motivation

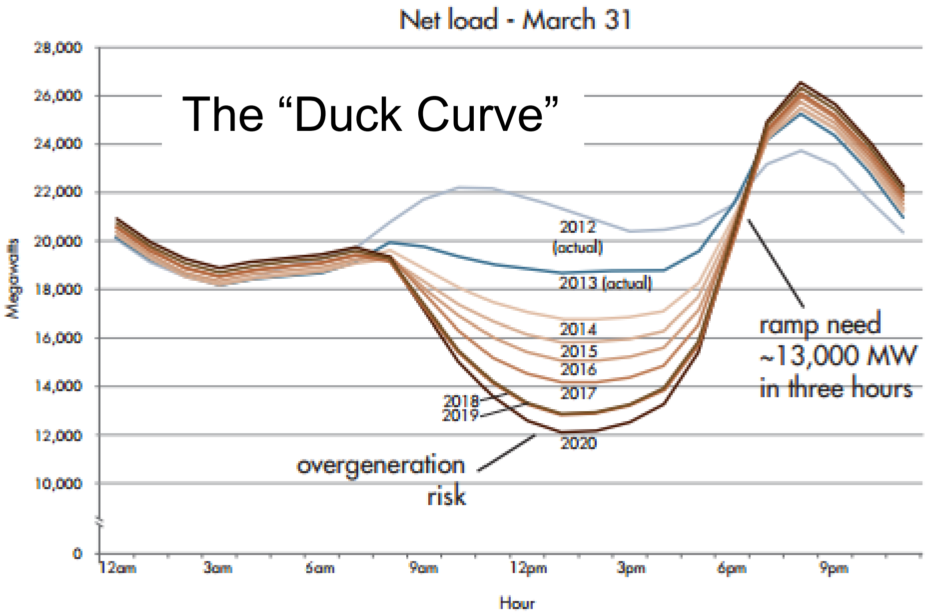
- Renewable energy technologies critical to energy future
  - Reduce carbon emissions and pollution
  - Secure and Sustainable Energy Future (SSEF Sandia mission area)



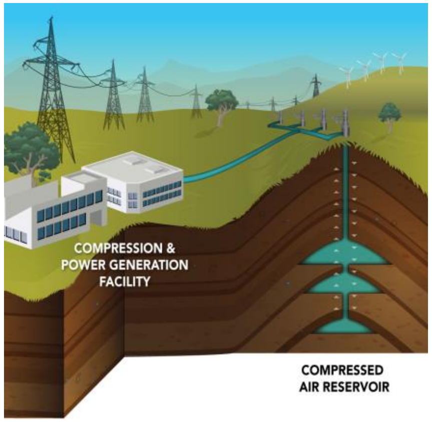
2015 – Warmest Global Year on Record (since 1880) – Colors indicate temperature anomalies (NASA/NOAA; 20 January 2016).

Problem Statement

- Current renewable energy sources are intermittent
    - Causes curtailment or negative pricing during mid-day
    - Cannot meet peak demand, even at high penetration
- Available energy storage options for solar PV & wind
    - Large-scale battery storage too expensive
        - \$0.20/kWh$_e$ - \$1.00/kWh$_e$
    - Compressed air and pumped hydro – geography and/or resource limited



Source: California Independent System Operator



Need

- Renewable energy technology with reliable, efficient, and inexpensive energy storage

→ Concentrating solar power (CSP) with thermal energy storage

- Current state-of-the-art CSP uses molten salt as storage media
  - Decomposes at temperatures < 600 ˚C
- Need higher temperatures to reduce costs
  - More efficient power cycles (supercritical CO_2 Brayton Cycles >700 ˚C)
  - Air Brayton Combined Cycles (>1000 ˚C)
  - Thermochemical Storage & Solar Fuels (>1000 ˚C)

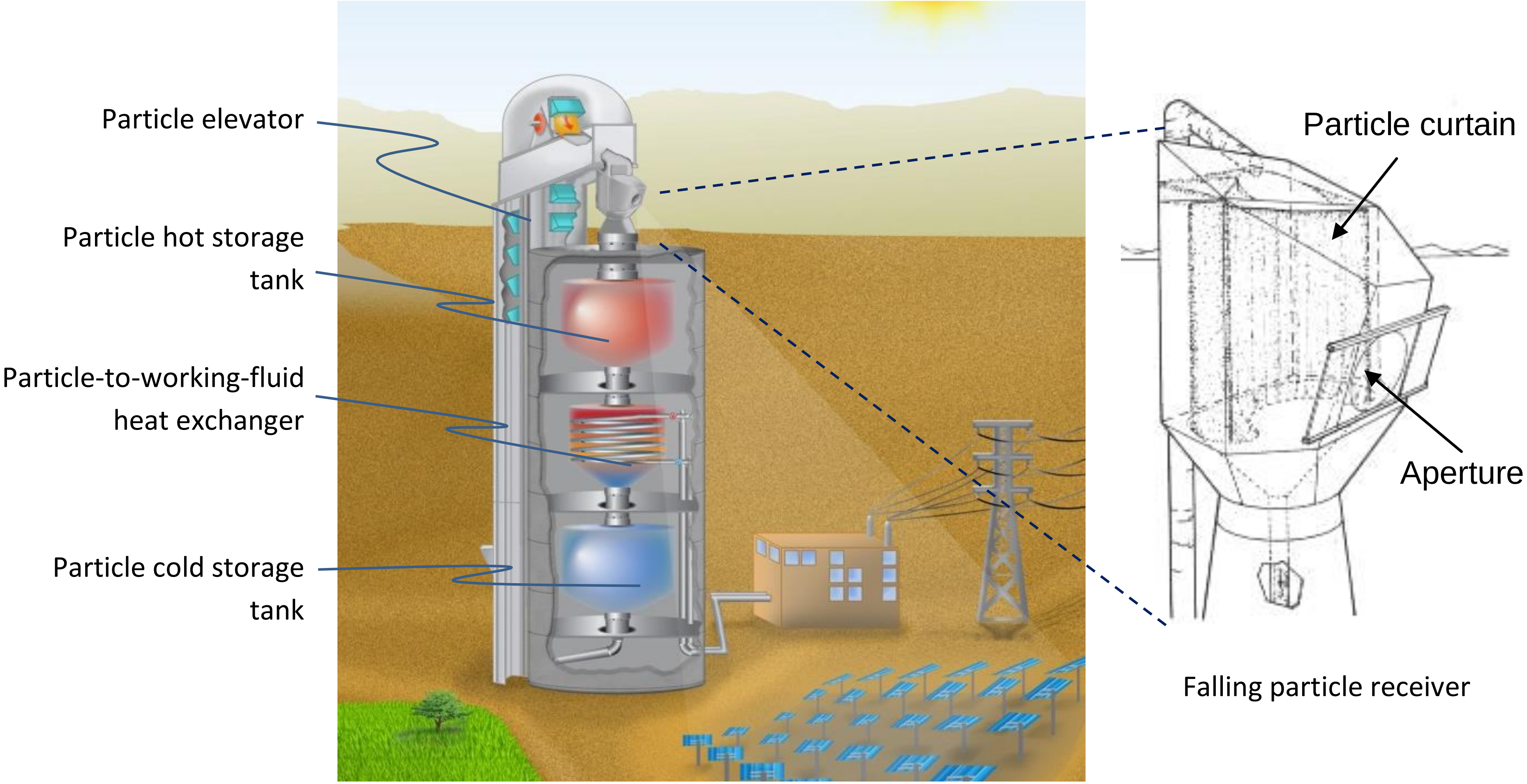
→ High-temperature particle receivers for concentrating solar power

Overview

- Why do we need it?
- How does it work?
- What is the impact?

High Temperature Falling Particle Receiver

(DOE SunShot Award FY13 – FY16)

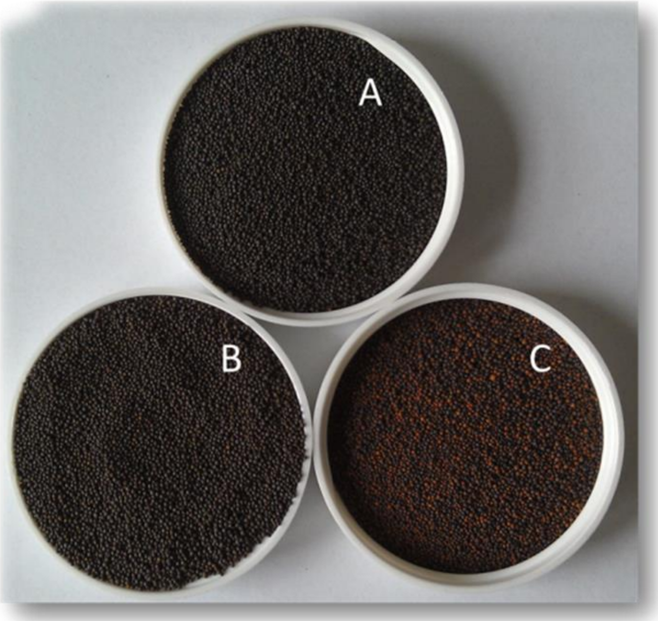


Goal: Achieve higher temperatures, higher efficiencies, and lower costs

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

⇨ particle **Power**



CARBO ceramic particles (“proppants”)

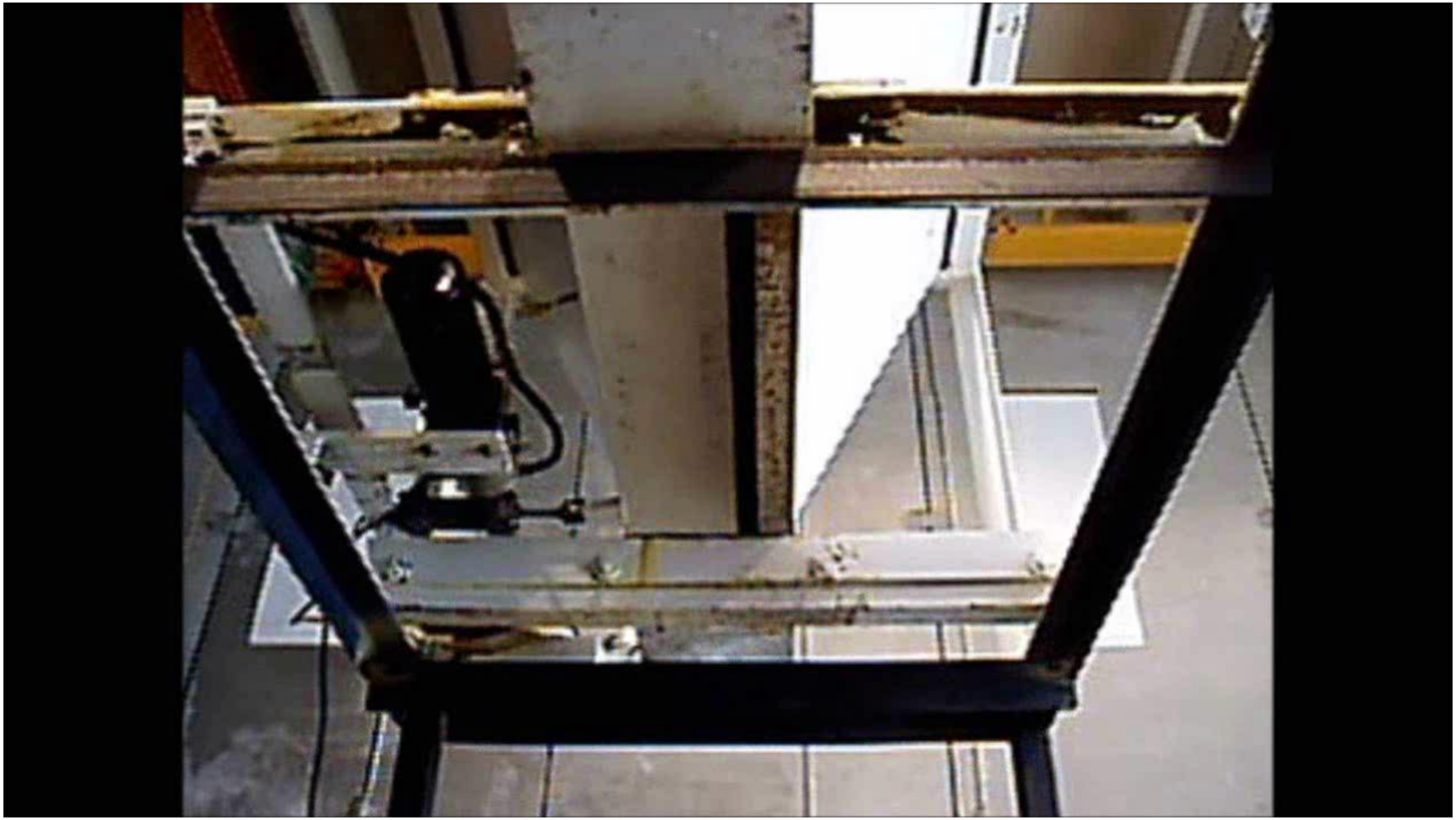
History

Particle Receiver Research at Sandia

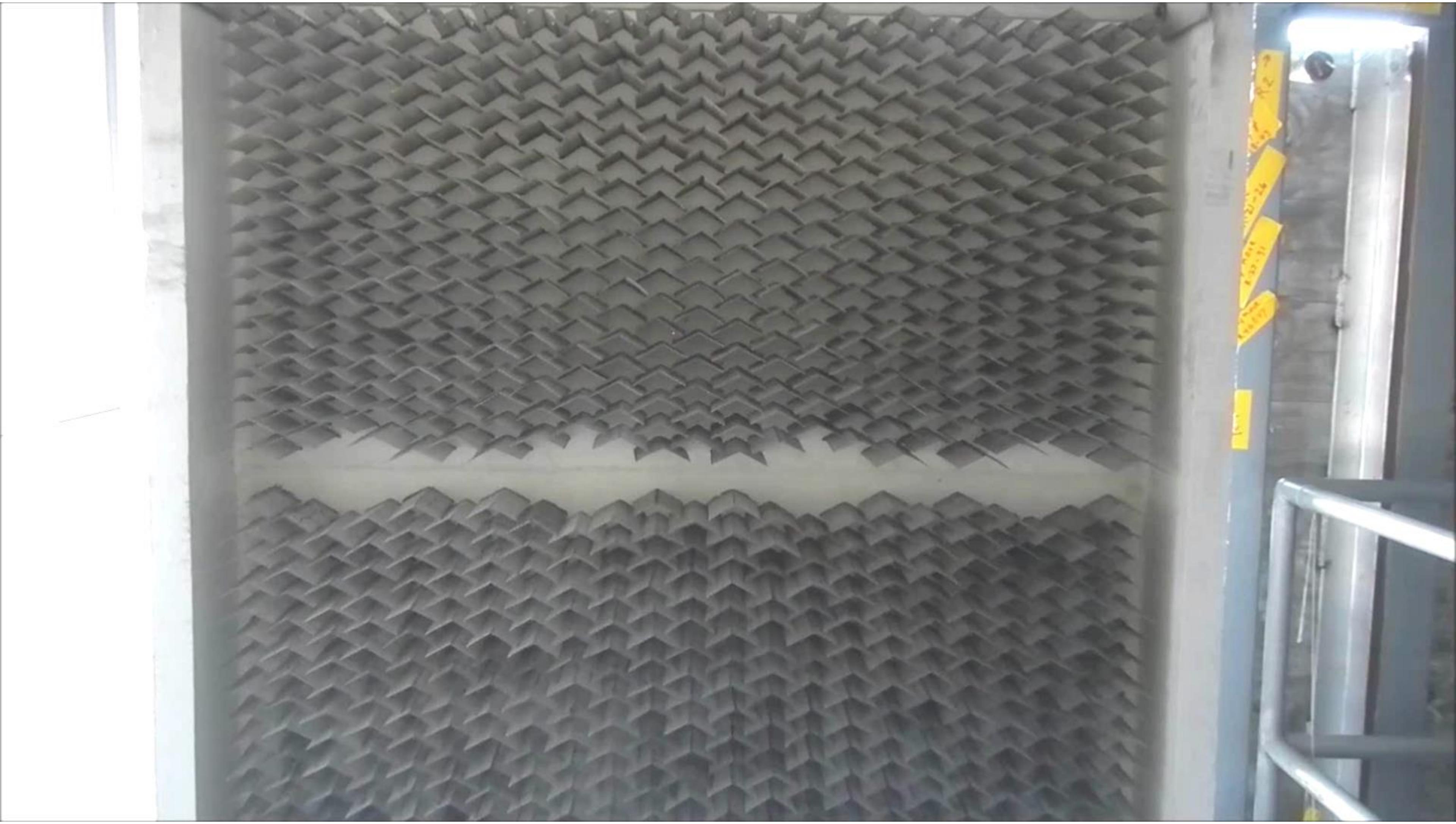
Jill Hruby
Sandia President

- 1980's
  - Feasibility study, modeling, bench-scale testing
- 2007 – 2008
  - First on-sun particle receiver test at Sandia
    - Batch run – no continuous operation
    - "Low" temperatures (up to ~300 ˚C)
    - Low thermal efficiency (~50%)
- Goal of current work (2013 – present)
  - Higher temperature (> 700 ˚C particle outlet)
  - Higher thermal efficiency (> 90%)
  - Continuous on-sun operation at 1 MW_t

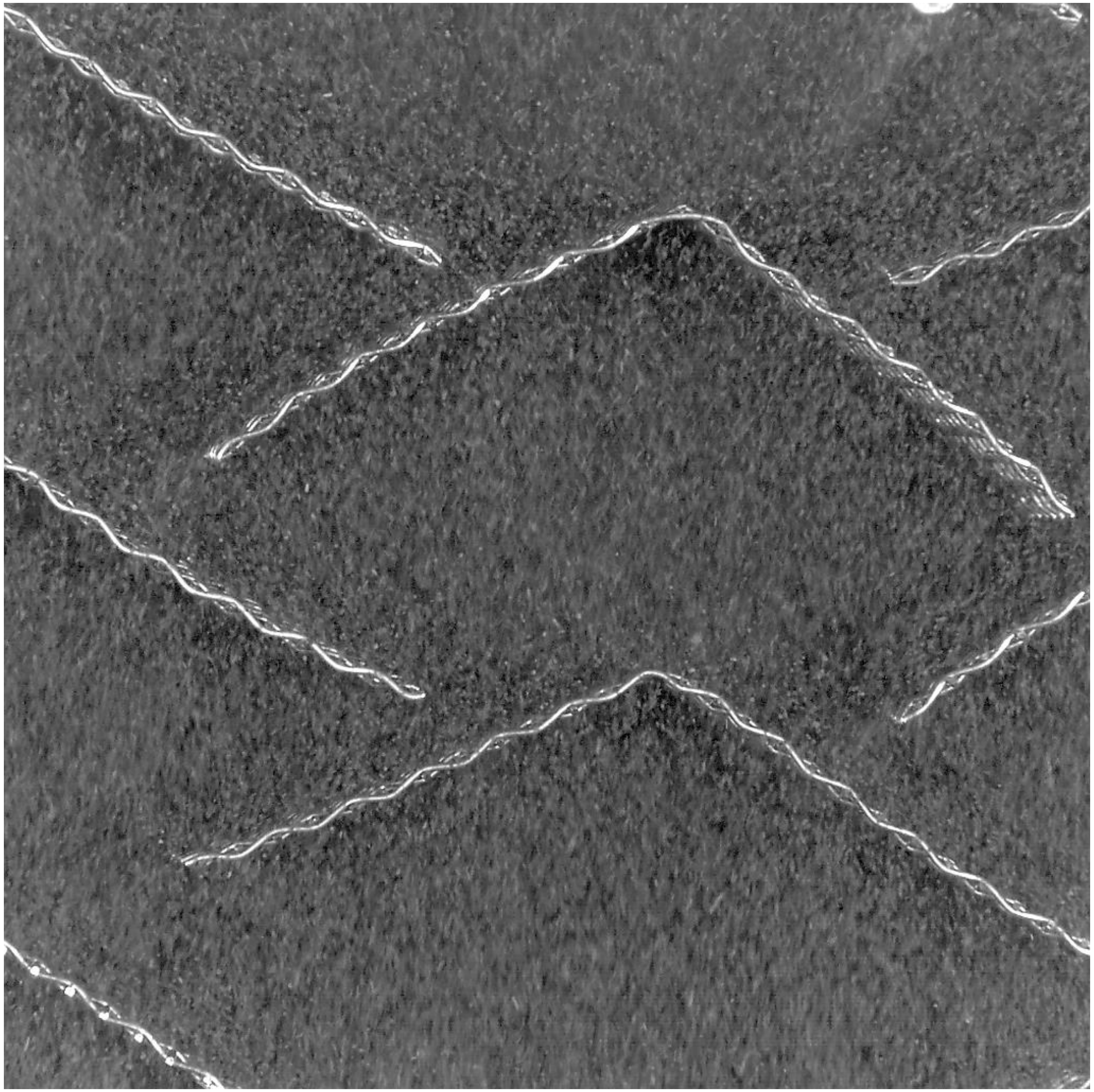
Particle Receiver Designs – Free Falling



Particle Receiver Designs – Pachinko



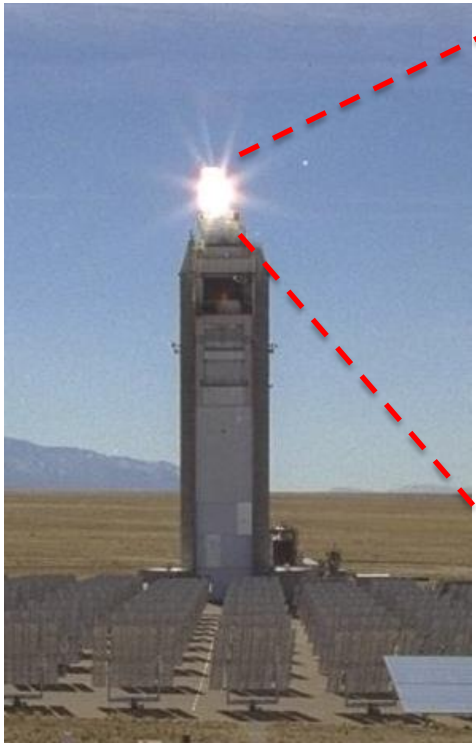
Particle Flow over Chevron Meshes

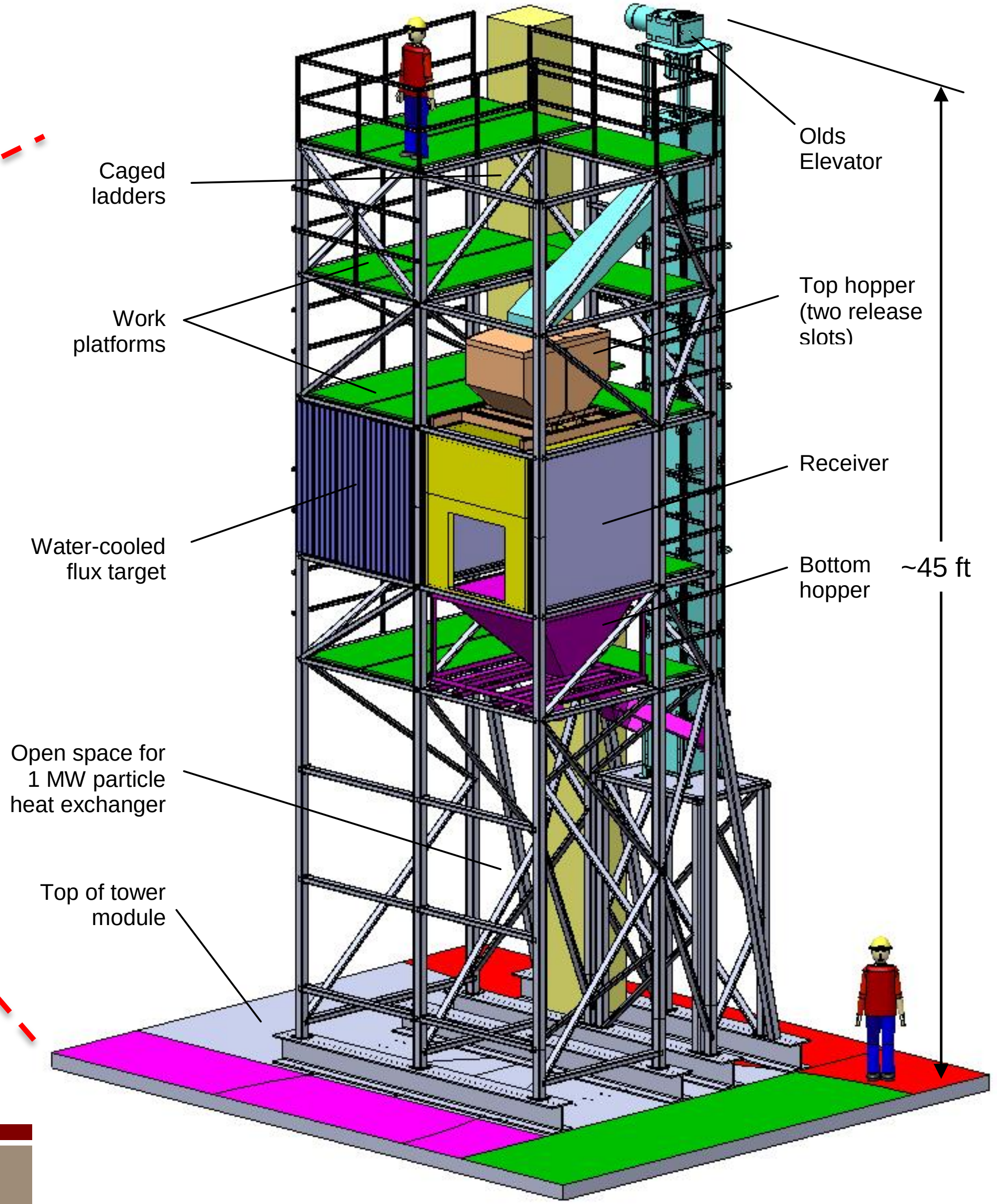


Pros: particle velocity reduced for increased residence time and heating

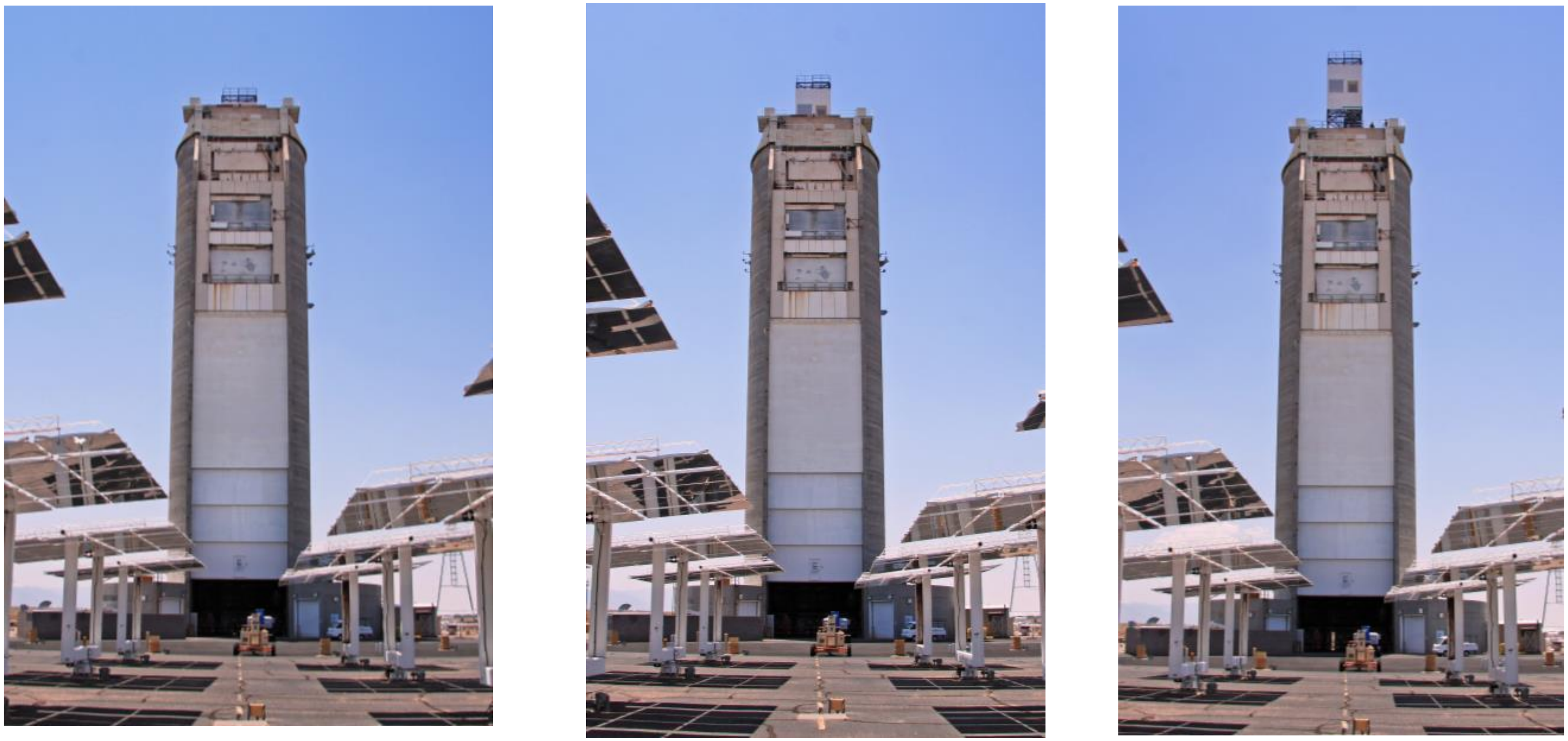
Cons: Mesh structures exposed to concentrated sunlight (~1000 suns)

Prototype System Design





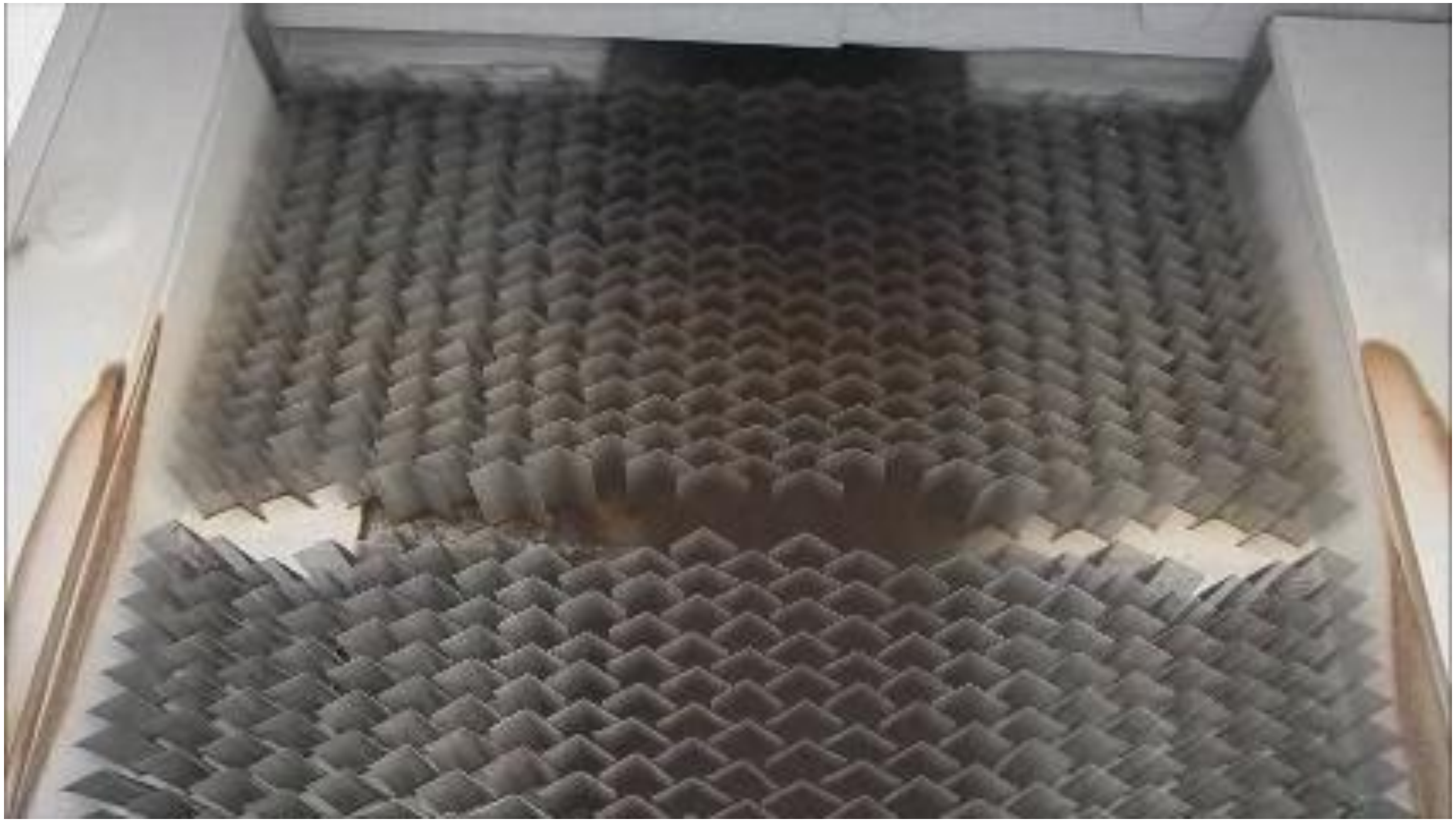
Lifting the system to the top of the tower



On-Sun Tower Testing

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

On-Sun Tower Testing



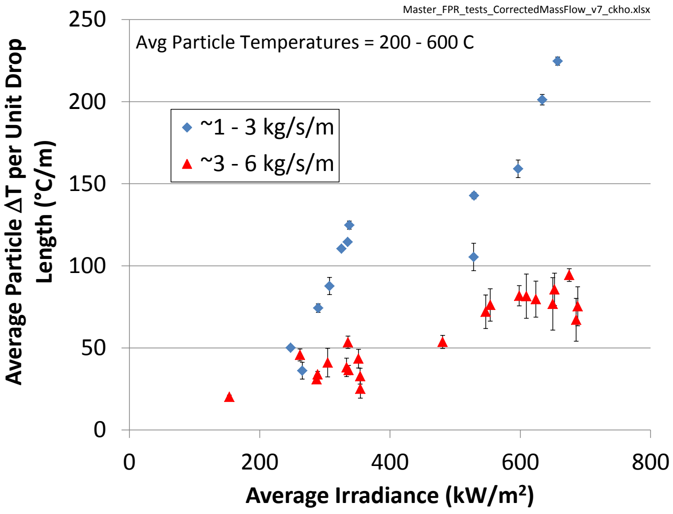
Particle Flow Through Mesh Structures
(June 25, 2015)

Overview

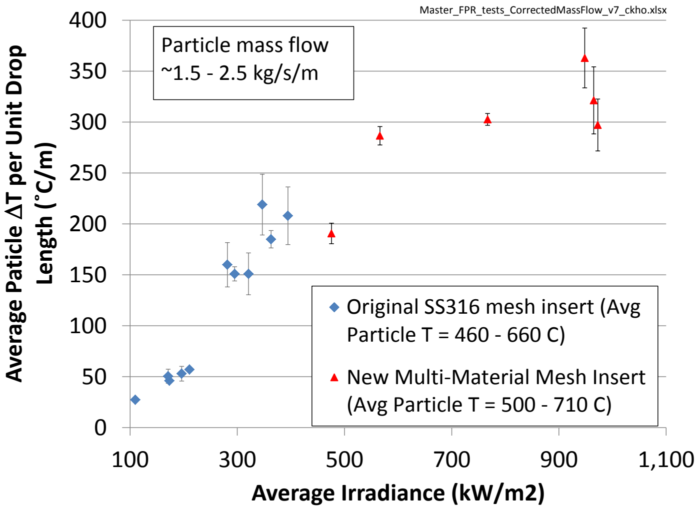
- Why do we need it?
- How does it work?
- What is the impact?

Impact - Performance

- Designed and constructed world's first continuously recirculating, on-sun, high-temperature particle receiver
  - Achieved average particle outlet temperatures > 800 ˚C
    - Peak particle outlet temperatures > 900 ˚C
  - Particle heating up to ~200 – 300 ˚C/(m of drop)
  - Thermal efficiency up to ~70% to 80%



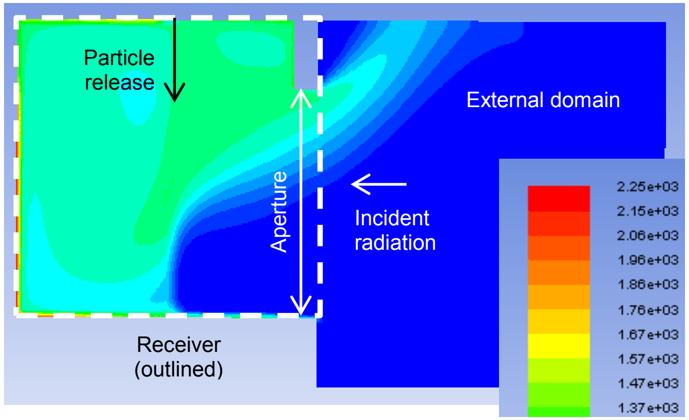
Free-Fall

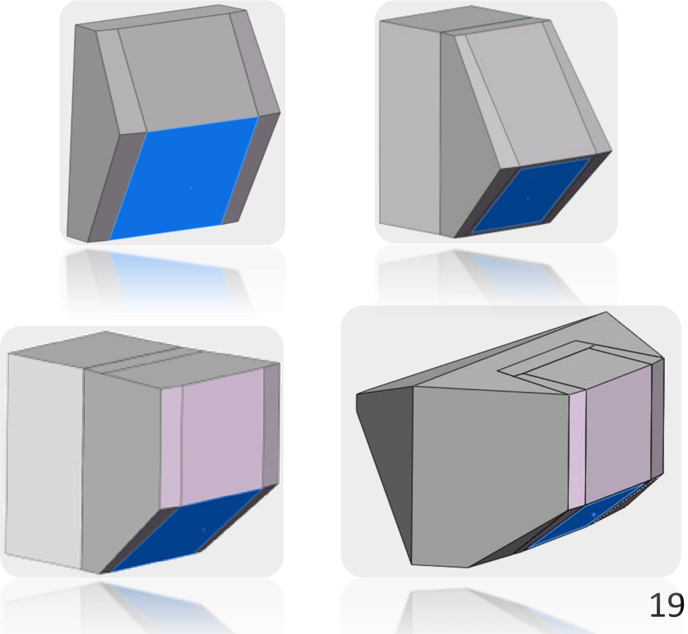


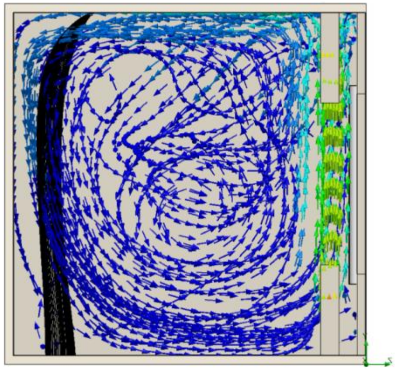
Obstructed-Flow

Impact – Advanced Modeling

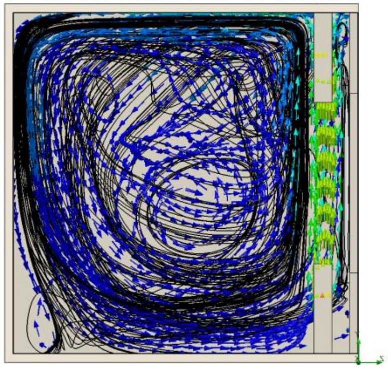
- Developed new coupled multi-physics, multiphase models
  - Radiation, convection, discrete phase particles, turbulence
  - Optimization of receiver geometry, particle size, mass flow rate, release patterns, air flow







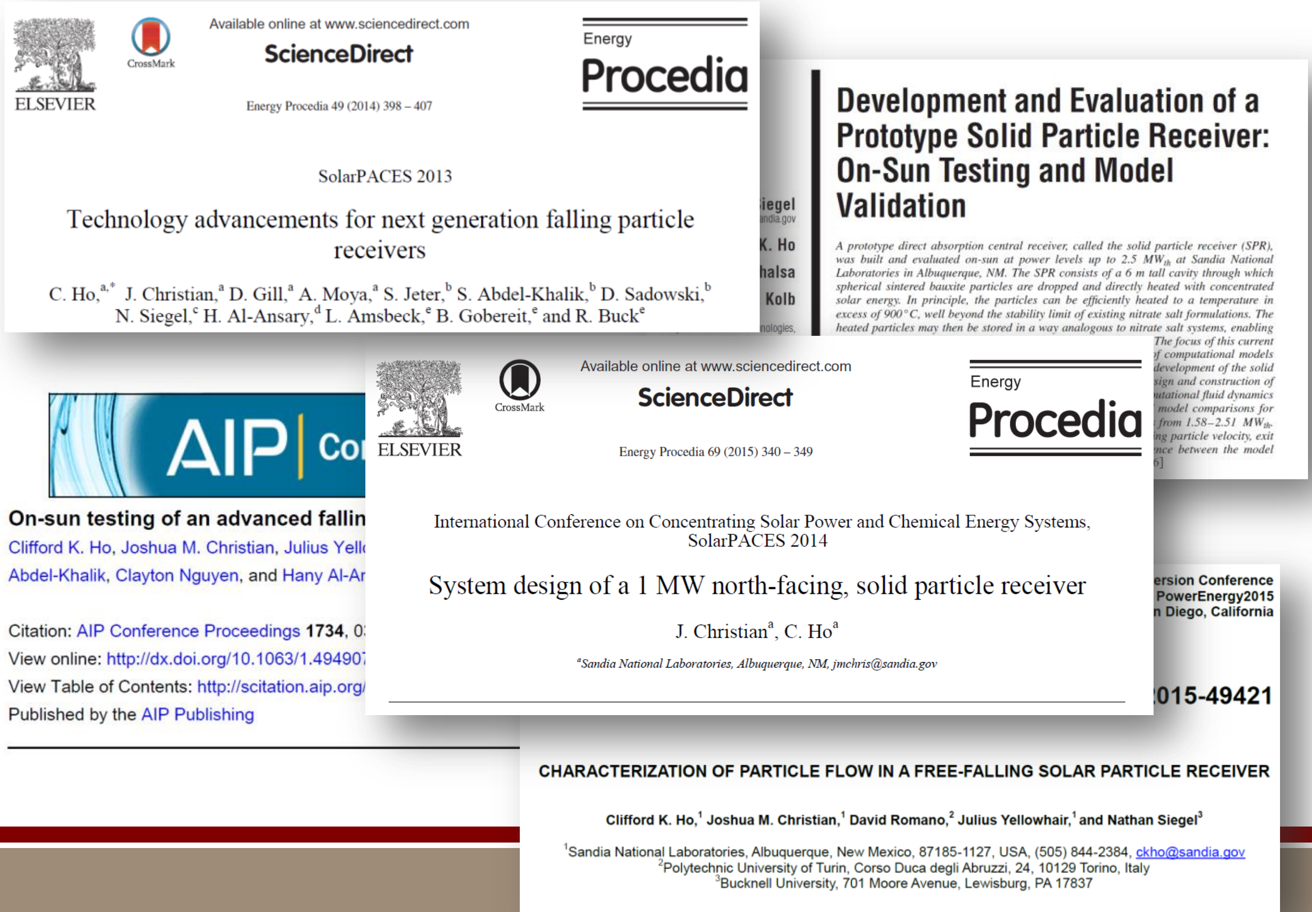
100 μm particle size



10 μm particle size

Publications & Patents

- 4 Patent Applications
- Over 20 peer-reviewed publications



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Energy Procedia 49 (2014) 398 – 407

Energy Procedia

SolarPACES 2013

Technology advancements for next generation falling particle receivers

C. Ho,[a,*] J. Christian,[a] D. Gill,[a] A. Moya,[a] S. Jeter,[b] S. Abdel-Khalik,[b] D. Sadowski,[b] N. Siegel,[c] H. Al-Ansary,[d] L. Amsbeck,[e] B. Gobereit,[e] and R. Buck[e]

Development and Evaluation of a Prototype Solid Particle Receiver: On-Sun Testing and Model Validation

iegel
andia.gov
K. Ho
halsa
Kolb
nologies,

A prototype direct absorption central receiver, called the solid particle receiver (SPR), was built and evaluated on-sun at power levels up to 2.5 MW_{th} at Sandia National Laboratories in Albuquerque, NM. The SPR consists of a 6 m tall cavity through which spherical sintered bauxite particles are dropped and directly heated with concentrated solar energy. In principle, the particles can be efficiently heated to a temperature in excess of 900°C, well beyond the stability limit of existing nitrate salt formulations. The heated particles may then be stored in a way analogous to nitrate salt systems, enabling

The focus of this current
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AIP | Co

On-sun testing of an advanced fallin

Clifford K. Ho, Joshua M. Christian, Julius Yell
Abdel-Khalik, Clayton Nguyen, and Hany Al-Ar

Citation: AIP Conference Proceedings **1734**, 0
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System design of a 1 MW north-facing, solid particle receiver

J. Christian[a], C. Ho[a]

[a]*Sandia National Laboratories, Albuquerque, NM, jmchris@sandia.gov*

ersion Conference
PowerEnergy2015
n Diego, California

015-49421

CHARACTERIZATION OF PARTICLE FLOW IN A FREE-FALLING SOLAR PARTICLE RECEIVER

Clifford K. Ho,[1] Joshua M. Christian,[1] David Romano,[2] Julius Yellowhair,[1] and Nathan Siegel[3]

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[2]Polytechnic University of Turin, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy
[3]Bucknell University, 701 Moore Avenue, Lewisburg, PA 17837

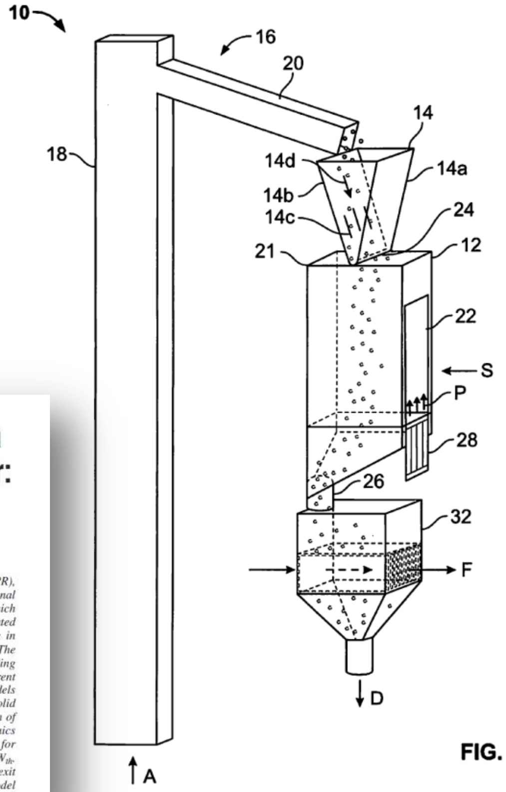

FIG. 1

Falling Particle Solar Receivers, U.S. Patent Application 15095738, 4/11/16

International Collaboration

- German Aerospace Center (DLR) – Partner on DOE project
- Australian Renewable Energy Agency and CSIRO (CRADA)
- Spain (Abengoa) (work for others)
- King Saud University – Partner on DOE project

300 kW_t Falling Particle Receiver Plant, Riyadh, Saudi Arabia

Commercial Interest

B&W
thebabcock&wilcoxcompany

VPE
VACUUM PROCESS ENGINEERING

SOLEX
THERMAL SCIENCE

BLACK & VEATCH

JENIKE® & JOHANSON
SCIENCE ENGINEERING DESIGN

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CARBO INDUSTRIAL CERAMICS

New Funding

- Two DOE SuNLaMP Projects - $6M (FY16 – FY18)
  - Particle/sCO2 heat exchanger and particle release patterns
- DOE APOLLO Project with Abengoa - $1M (Sandia share)
  - Integrated particle receiver for combined cycle plant
- DOE ELEMENTS Project - $4M (Orgs. 6124 and 1815)
  - Thermochemical particle storage

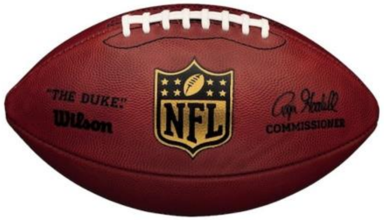
- DOE Next Generation CSP Plant Demonstration – up to $50M
  - Particle receiver is one of two options being pursued

Acknowledgments

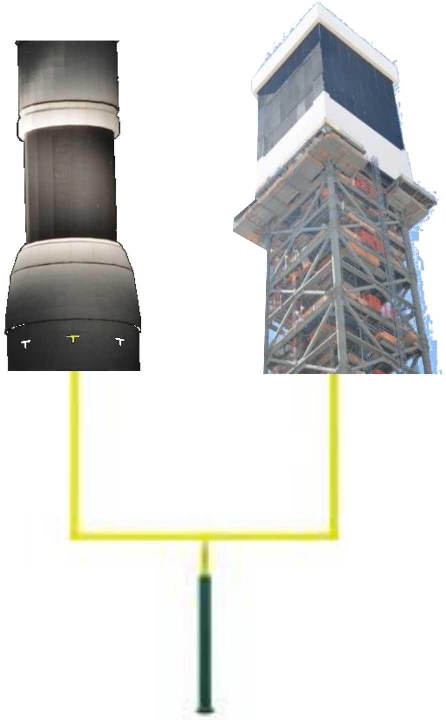
Award # DE-EE0000595-1558

- **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

Why do football coaches love CSP engineers?

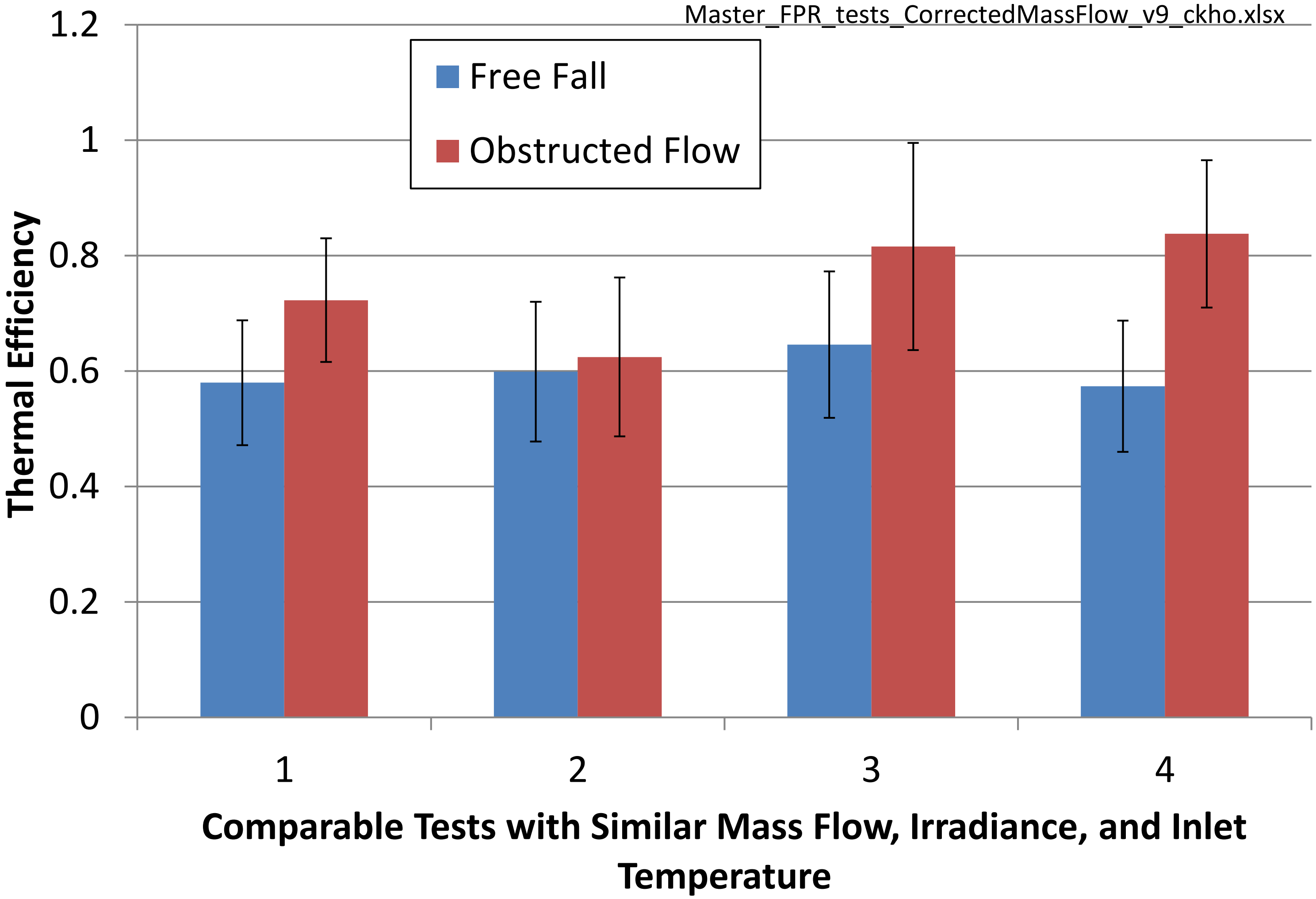


- Because we make great receivers!

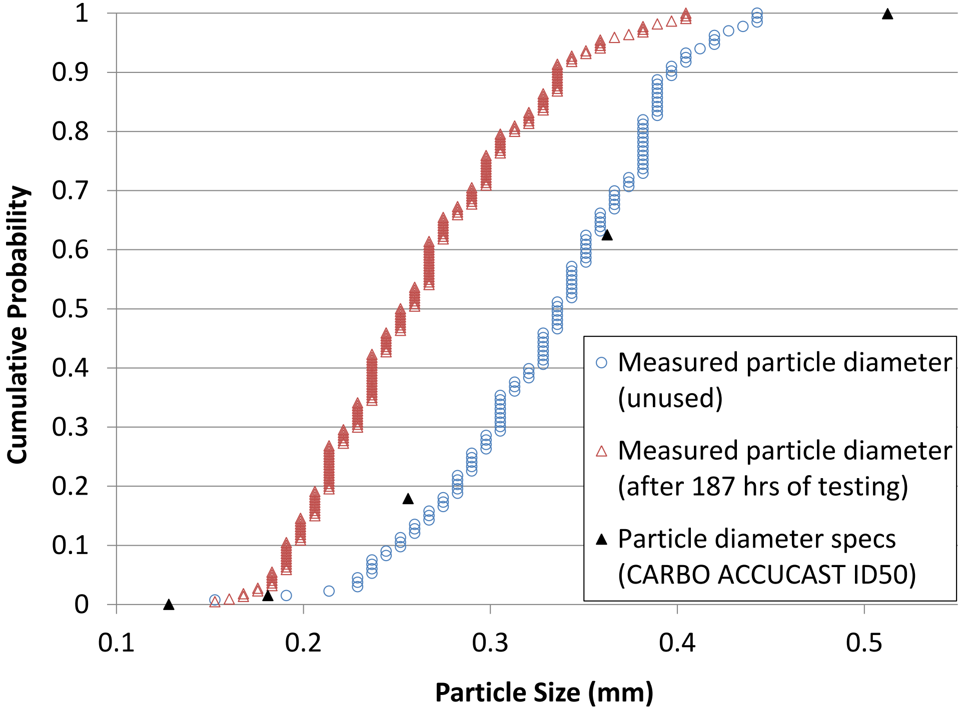


Backup Slides

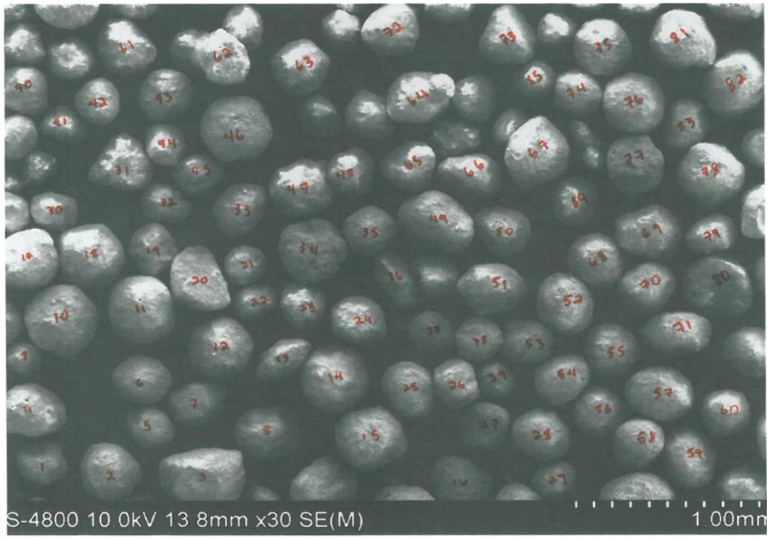
Free-Fall vs. Obstructed Flow



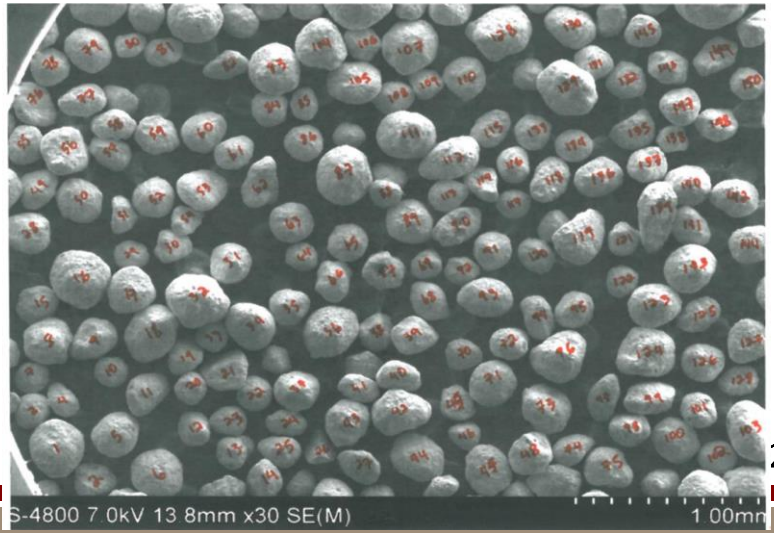
SEM Images of Used and Unused Particles



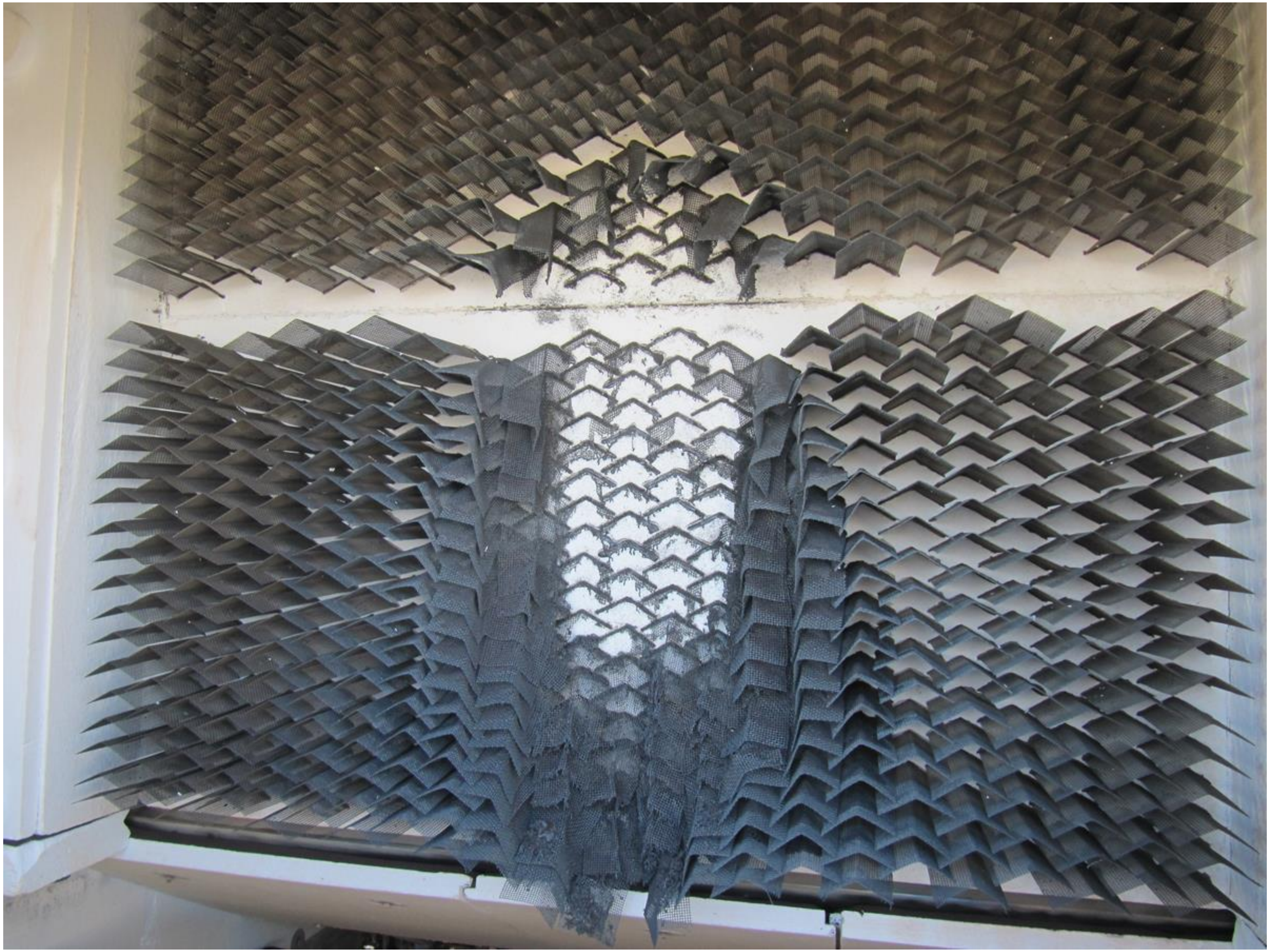
Unused



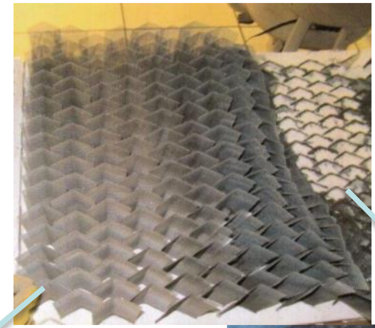
Used

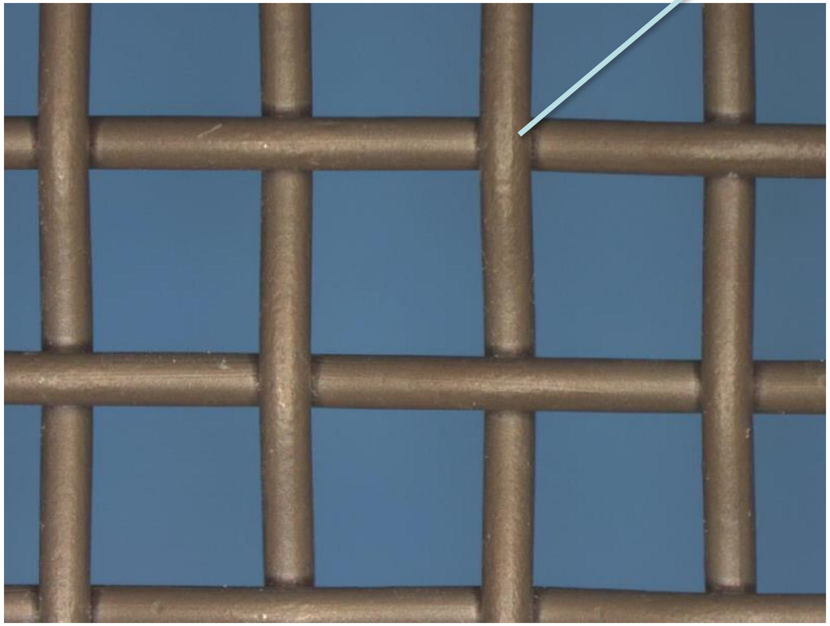


July 24, 2015 – Nearly 700 suns

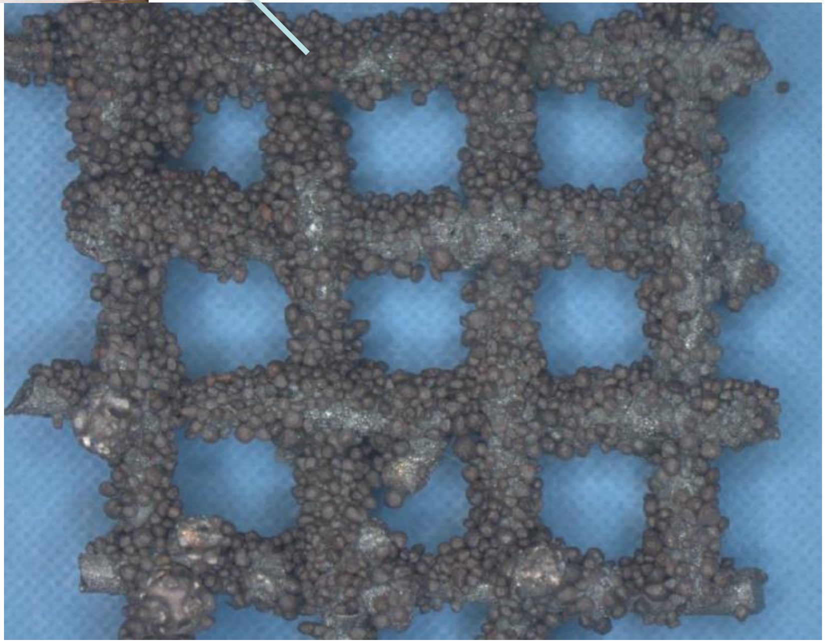


SS316 Mesh Failure Analysis



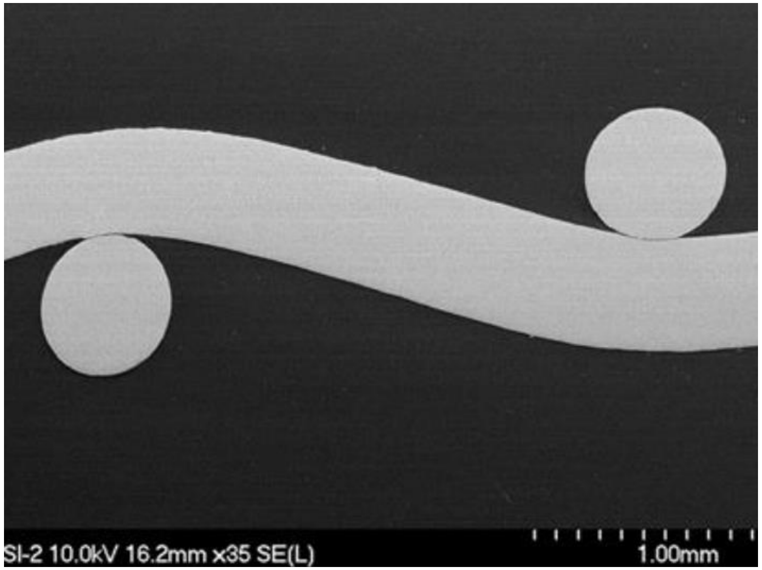


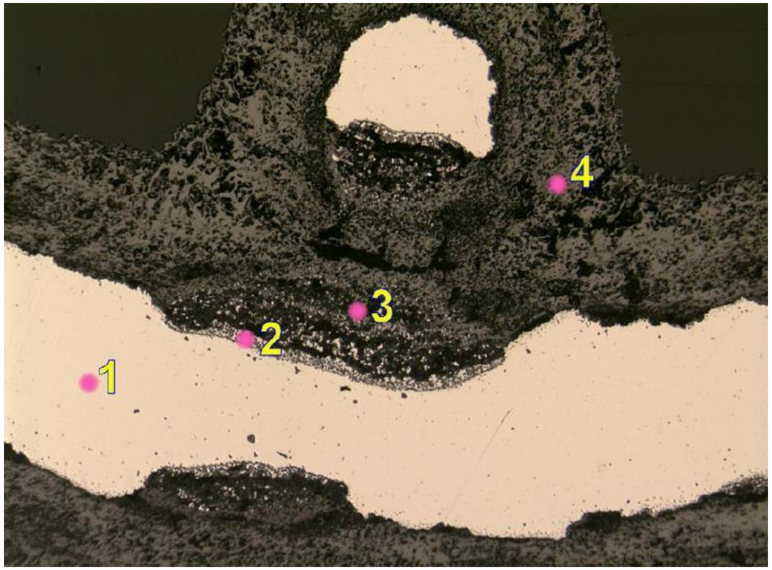
Mesh located far from failed region



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

SS316 Mesh Failure Analysis



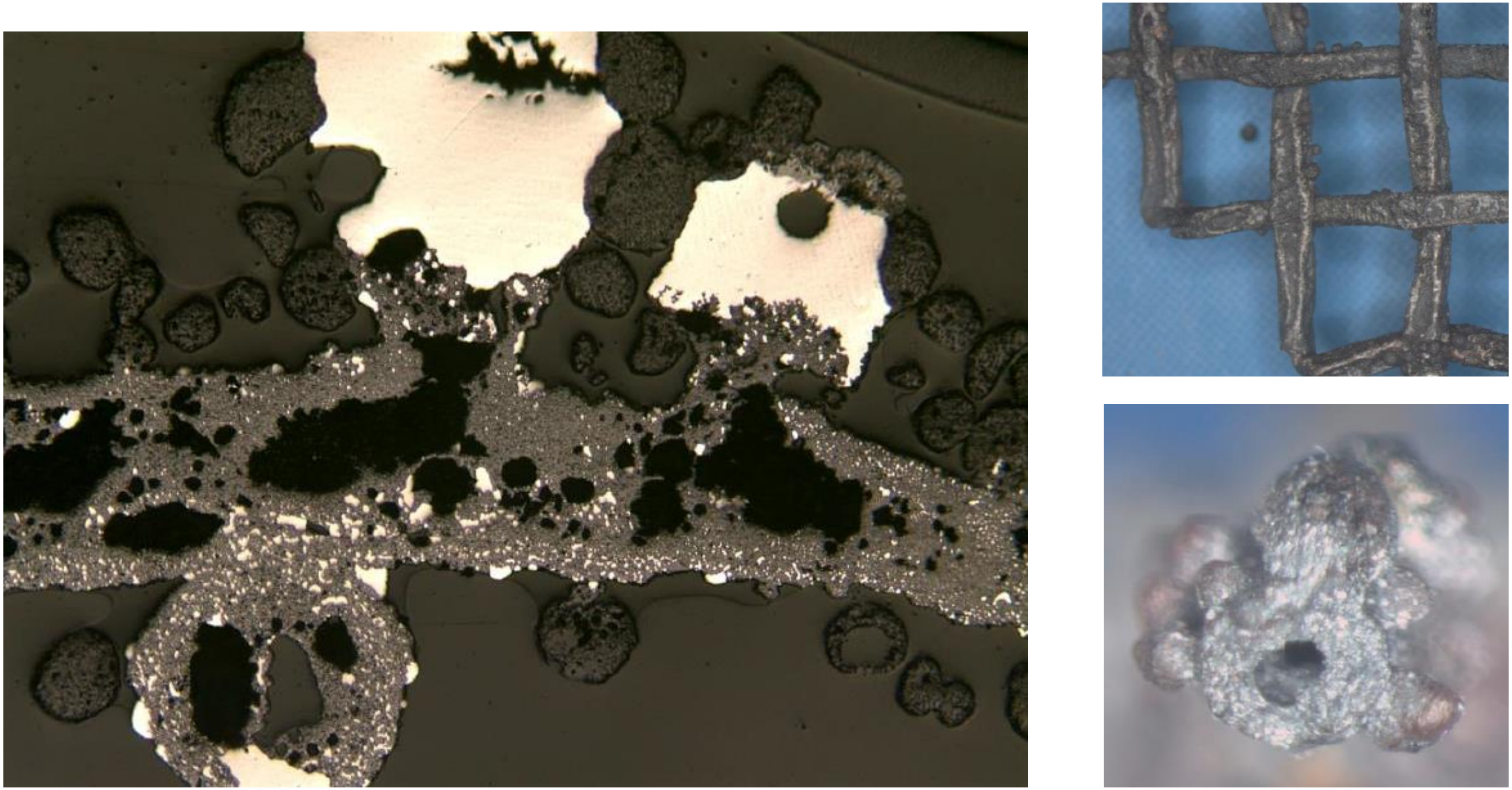


Top left: cross-sectional view of intact wire mesh

Top right: cross-sectional view of oxidized wire mesh

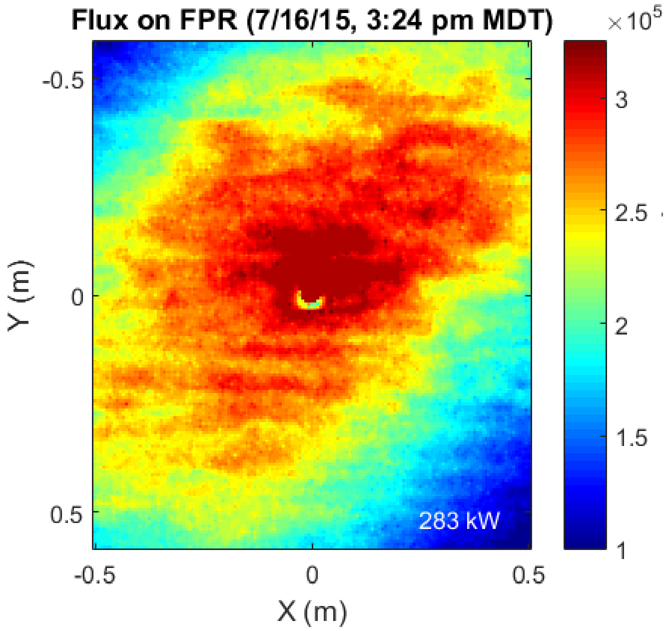
	Fe	Cr	Ni	Mo	O	Al	Si
	(Wt% EDS semi-quant, standardless EDS)						
Location 1 **Wire core**	67	20	6.7	5.2	-	-	-
Location 2 **“intermetallic layer”**	19	4.45	44	11	19	1.64	1.34
Location 3 **Oxidized zone**	22	18	4.39	5.26	48	1.1	1.75
Location 4 **Oxidized zone**	34	10	2.89	2.32	48	-	1.45

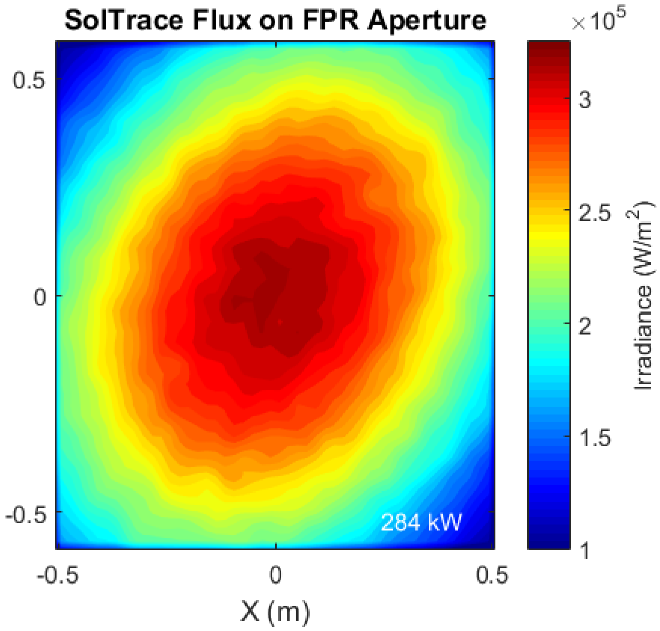
SS316 Mesh Failure Analysis

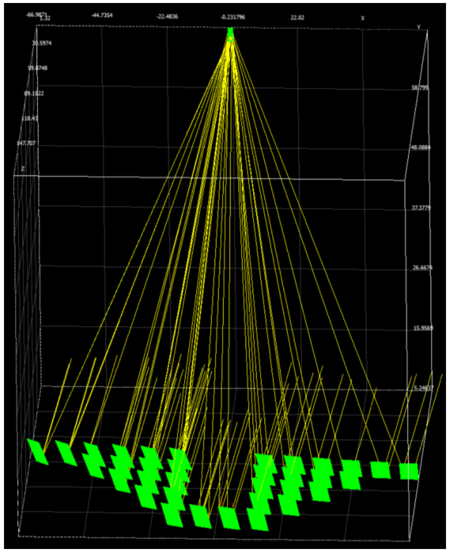


Cross-sectional view of oxidized wire mesh; wire ruptured and “leaked” molten steel out of oxidized shell (white is stainless steel, rough gray area is oxidized mesh)

Irradiance Measurements



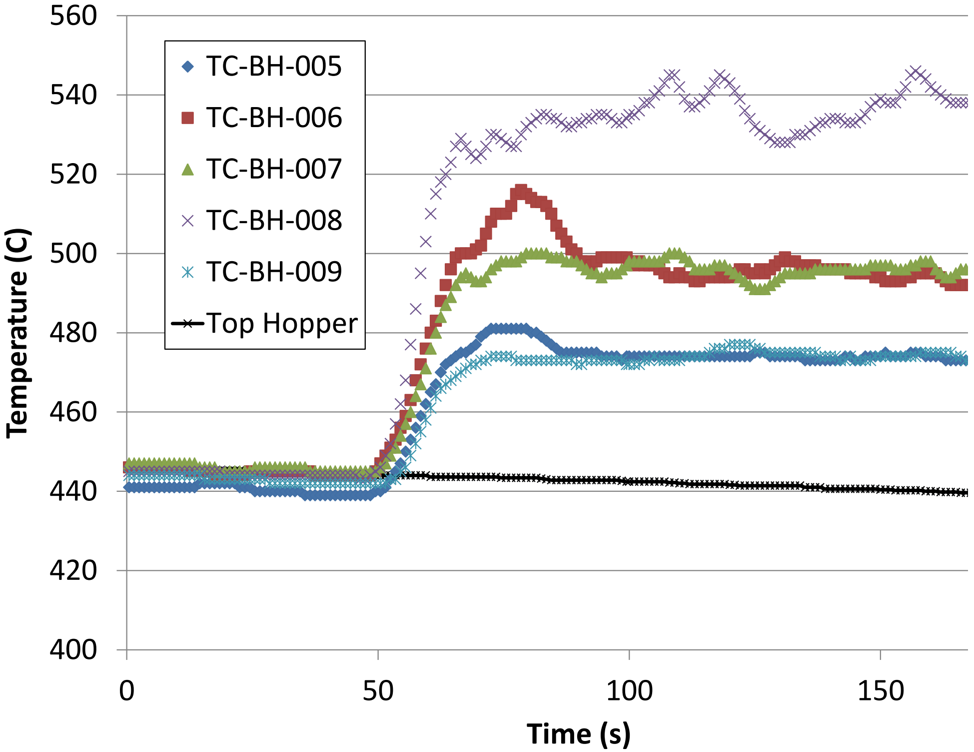


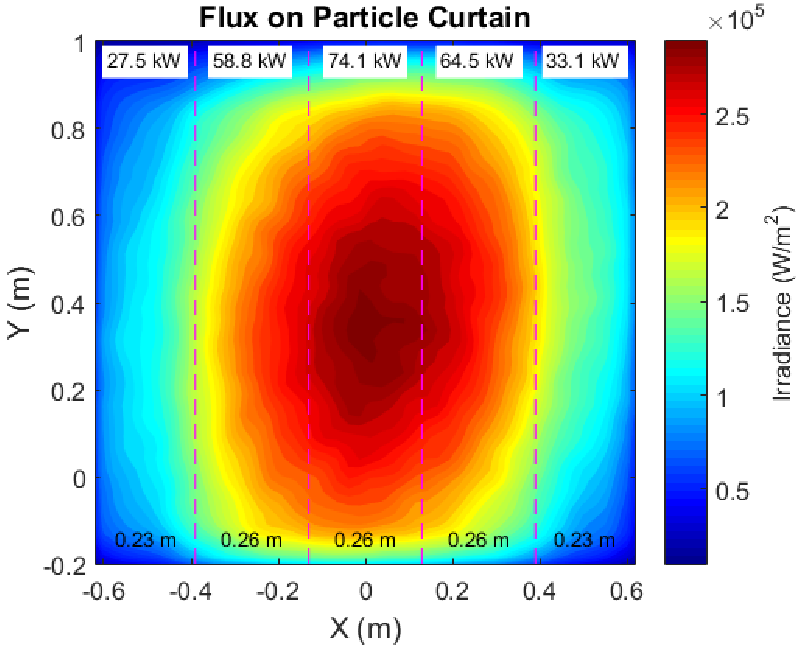


Measured

Simulated using Ray Tracing (SolTrace)

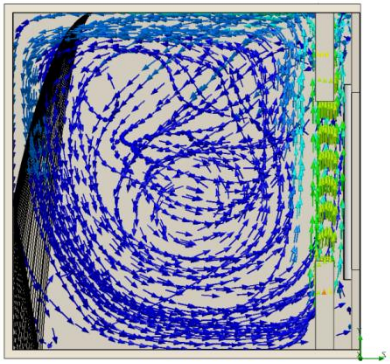
Temperature Measurements



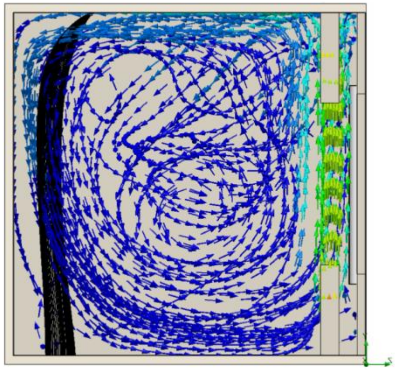


Air Curtain Modeling (SNL)

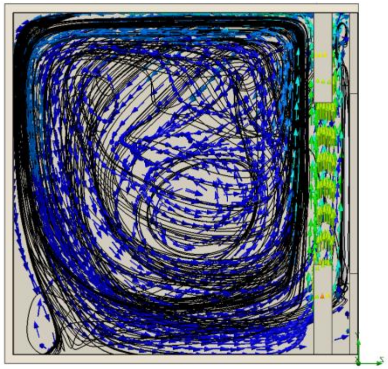
- Evaluate use of air recirculation along aperture to reduce heat loss and impacts of external wind
  - Investigate particle size, location, particle flow rate, air flow rate, external wind



I mm particle size



100 μm particle size



10 μm particle size

Novel Particle Curtain Designs

- Develop new particle release configurations that increase solar absorptance and thermal efficiency

U.S. Provisional Patent 62145136/SD12934.0
April 9, 2015