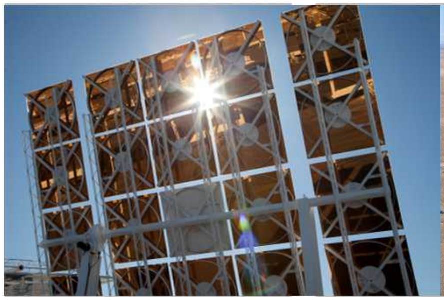
SAND2016-2701PE

Exceptional service in the national interest

Sandia National Laboratories



# Overview of Concentrating Solar Power and Research Needs

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SAND2013-3160P

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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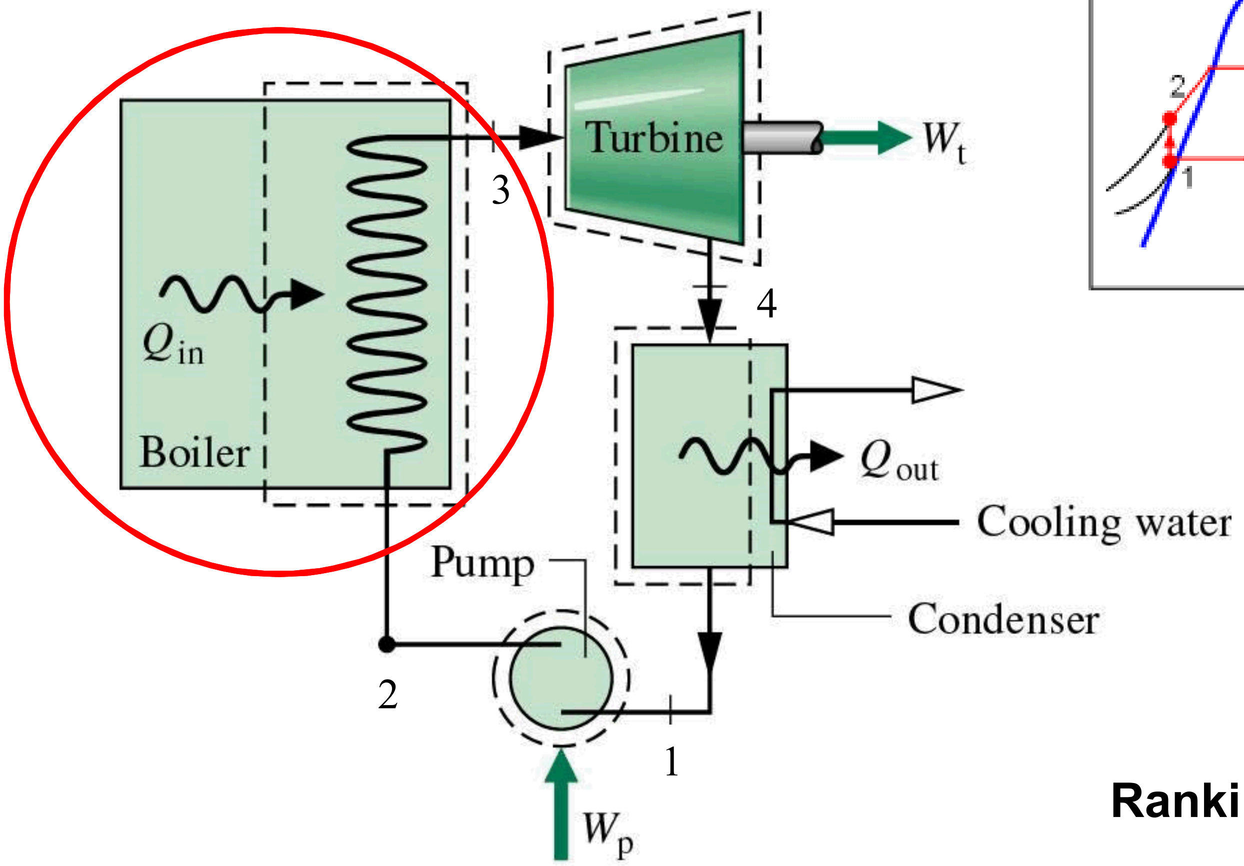
# Outline

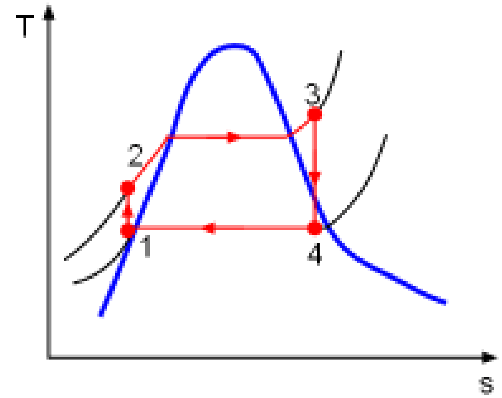
- **What is Concentrating Solar Power (CSP)?**
- **Economics of CSP**
- **CSP Research Needs**
- **Summary**

Sandia National Laboratories

# What is Concentrating Solar Power (CSP)?

CSP provides heat for a power cycle

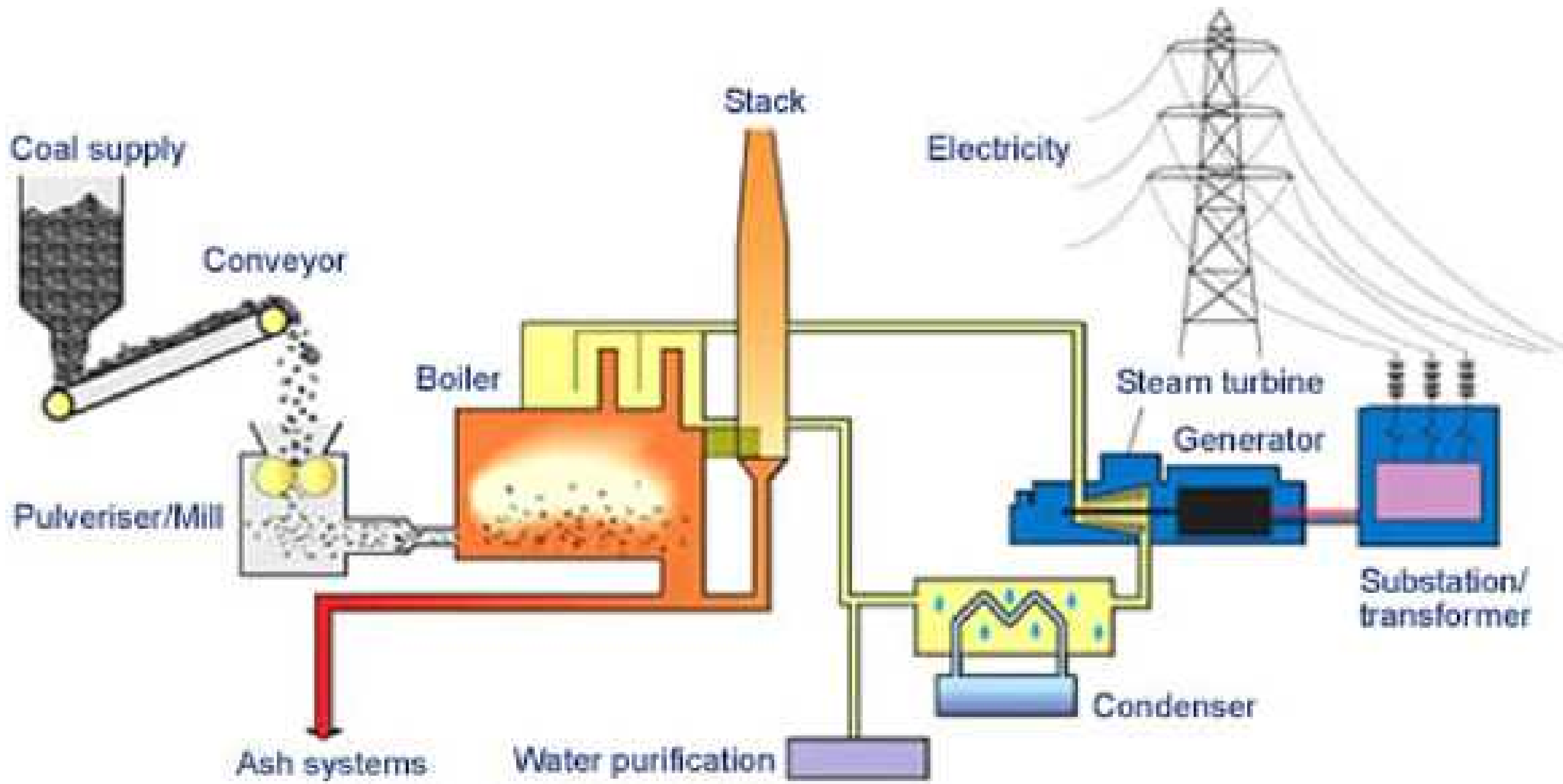



**Rankine Cycle**

# What is Concentrating Solar Power (CSP)?

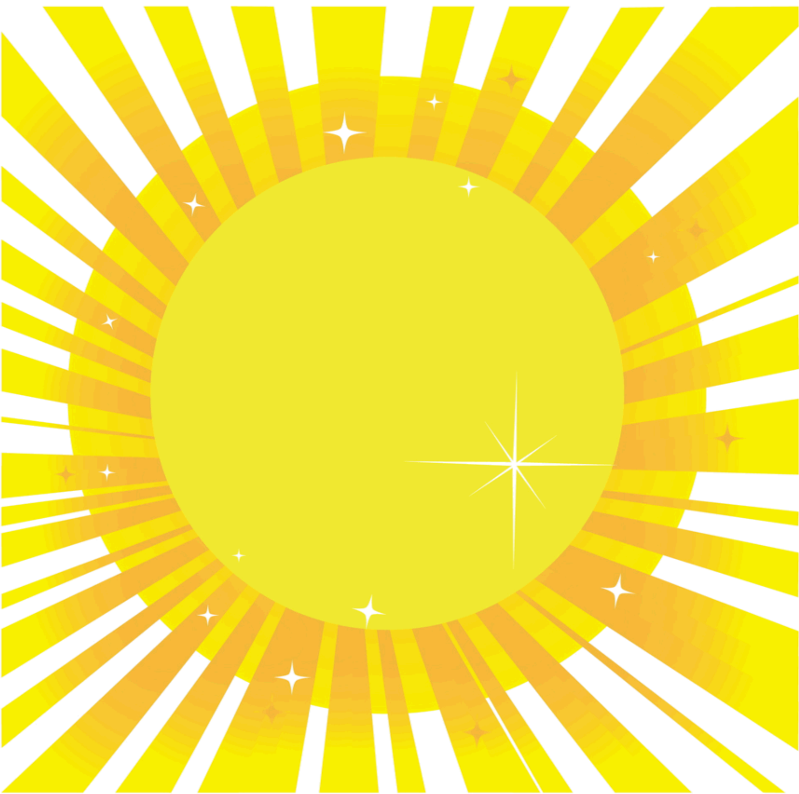
Conventional power plants burn fossil fuels (e.g., coal, natural gas) or use radioactive decay (nuclear power) to generate heat for the power cycle

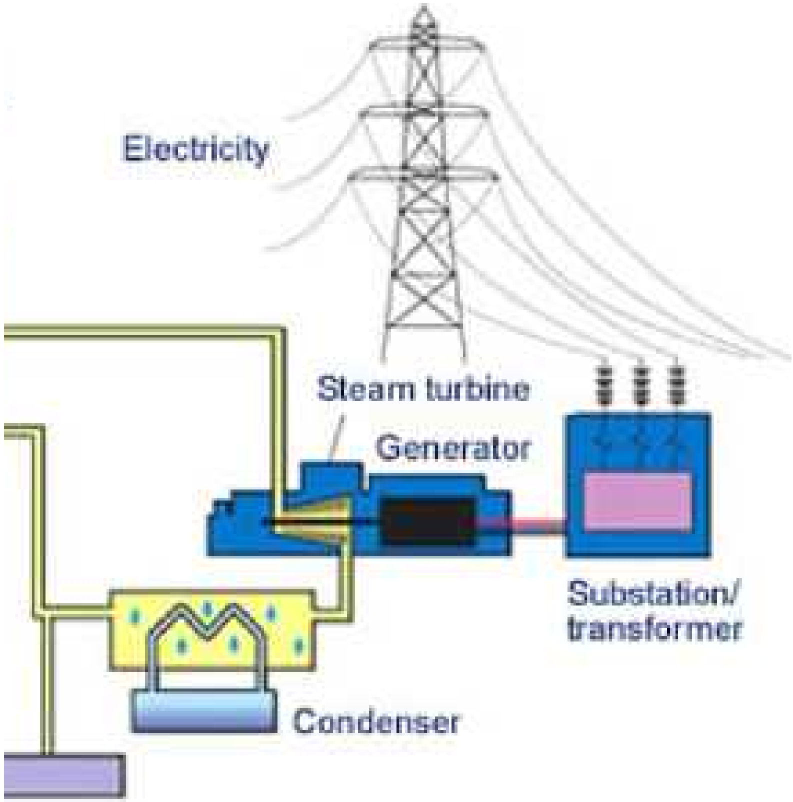



Coal-Fired Power Plant

# What is Concentrating Solar Power (CSP)?

CSP uses concentrated heat from the sun as an alternative heat source for the power cycle





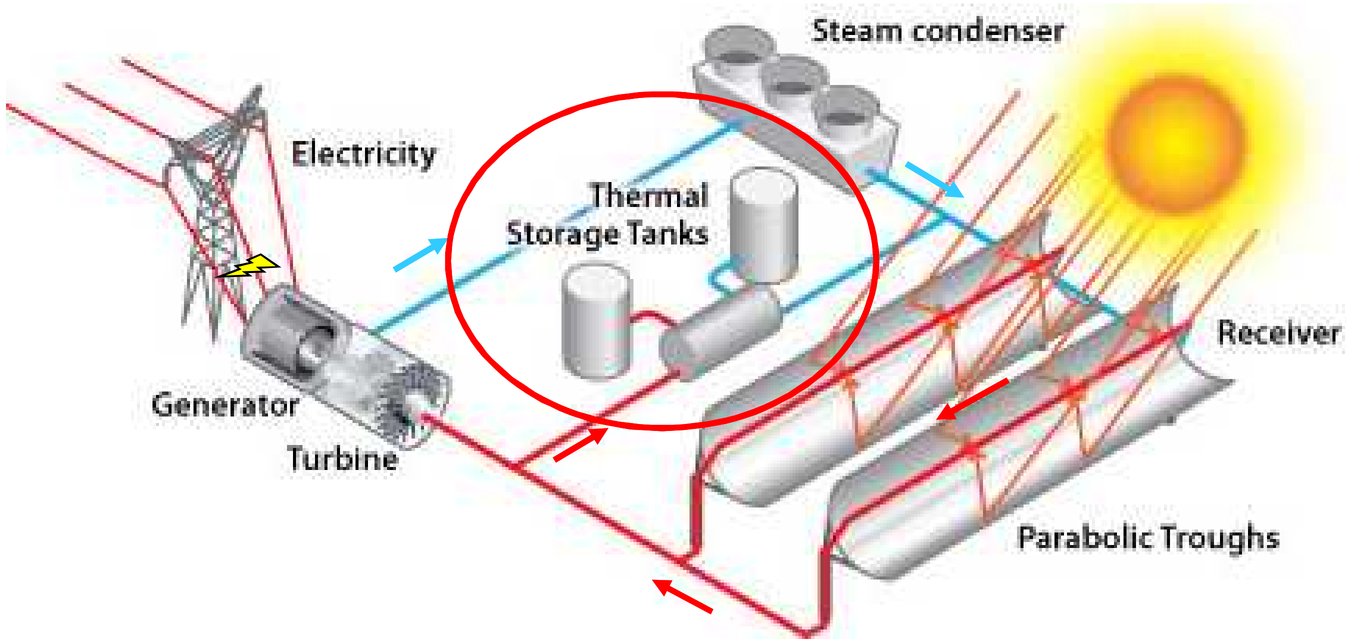

Concentrating Solar Power

# How Does CSP Work?

- Concentrating solar power uses mirrors to concentrate the sun’s energy onto a receiver to heat a fluid (e.g., steam), which turns a turbine and generator to produce electricity

# How Does CSP Work?

- Concentrating solar power uses mirrors to concentrate the sun's energy onto a receiver to heat a fluid (e.g., steam), which turns a turbine and generator to produce electricity

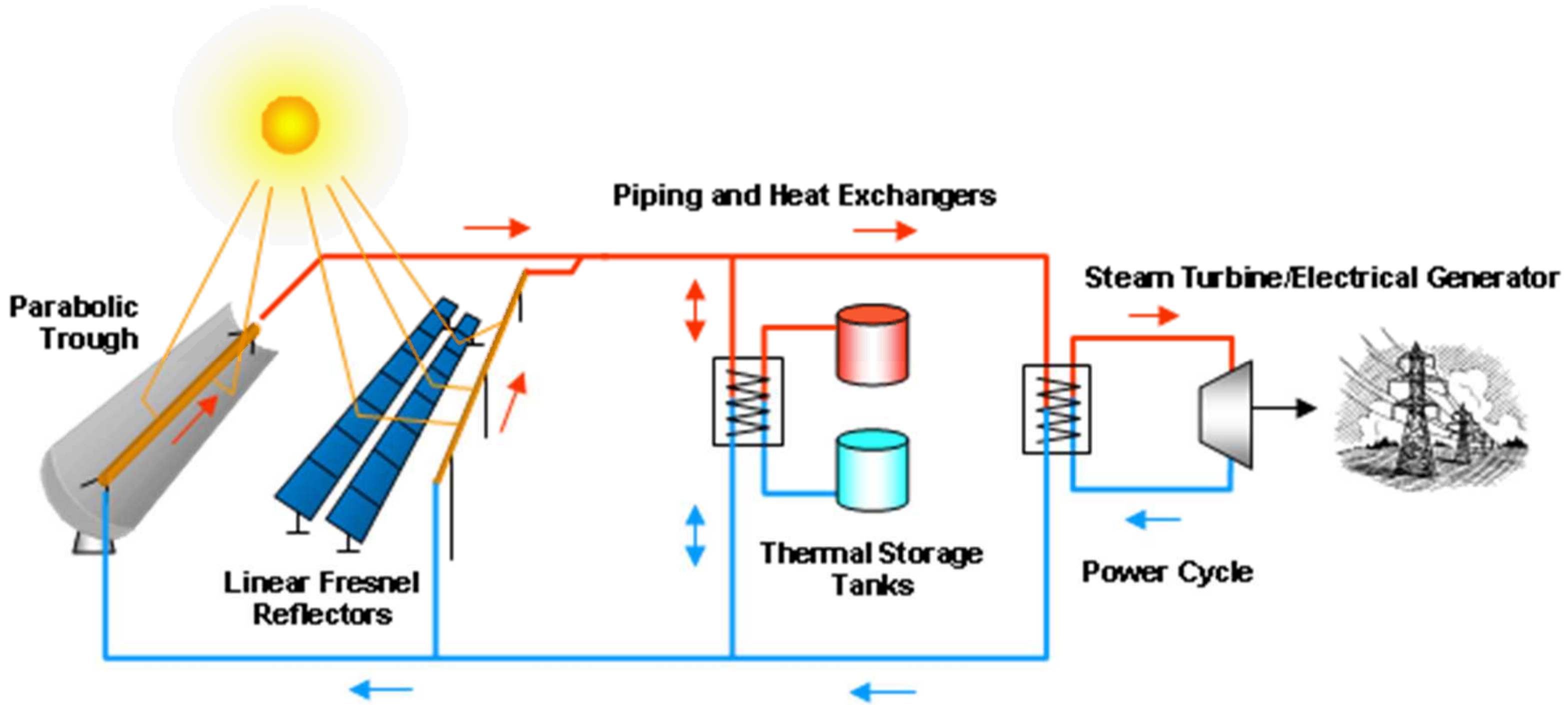


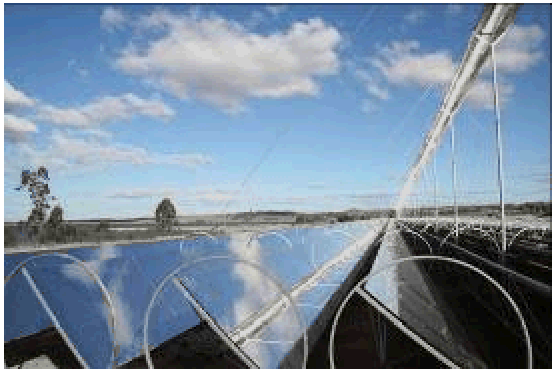

From the U.S. DOE Solar Energy Technologies Program Web Site:
http://www.eere.energy.gov/basics/renewable_energy/linear_concentrator.html

# CSP Technologies

- Line Focus
  - Parabolic Troughs
  - Linear Fresnel
- Central Receivers “Power Towers”
- Dish Engines

# Line Focus Systems

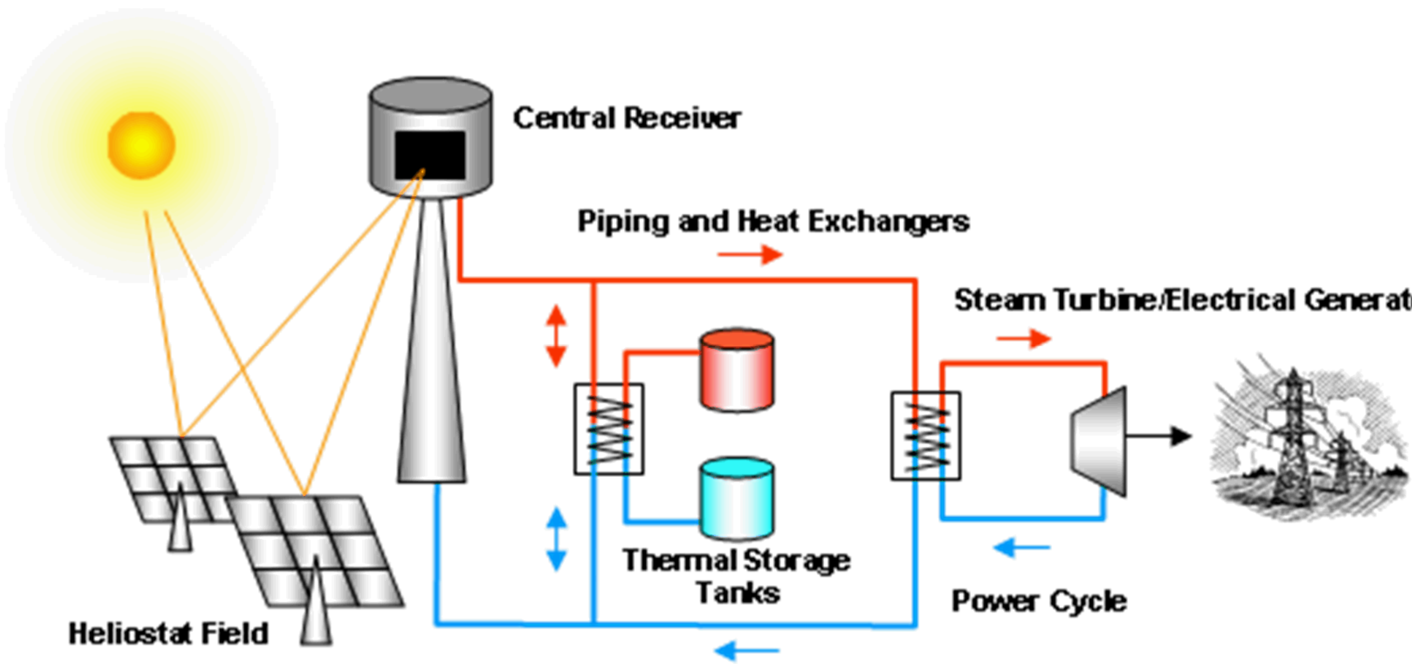


Parabolic trough (left) and linear Fresnel (right) collector systems (photos from http://en.wikipedia.org/wiki/Solar_thermal_energy)

# Central Receivers

## "Power Towers"



# Central Receivers

## “Power Towers”

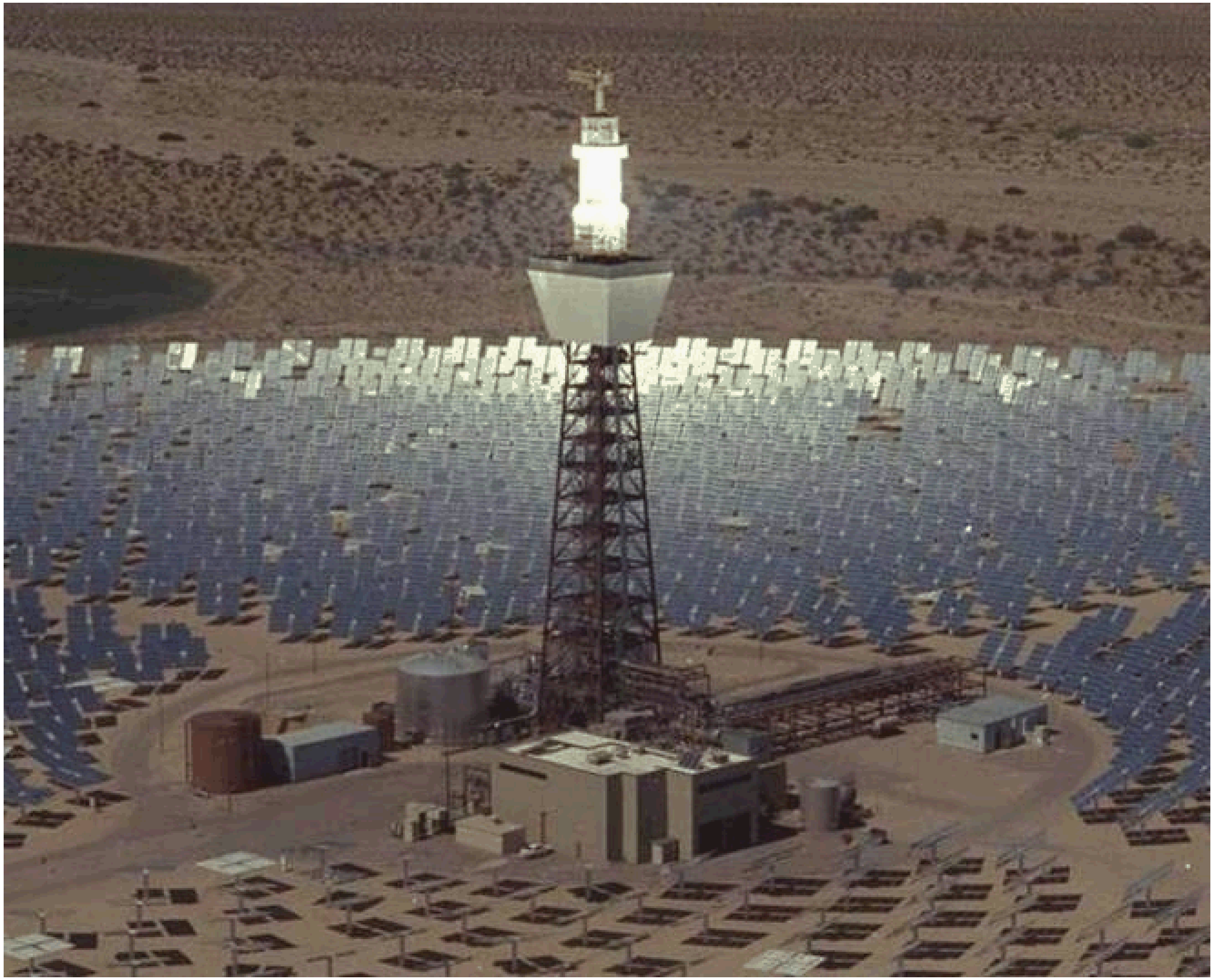


Photo of Solar Two power tower plant in operation in Daggett, CA (photo from Sandia National Laboratories, photo 2897)

# Dish/Engine Systems

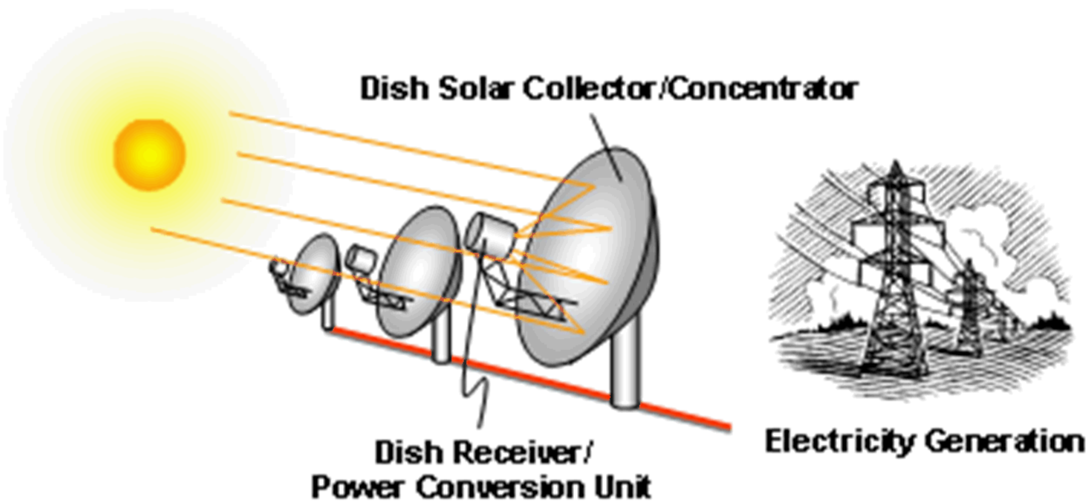
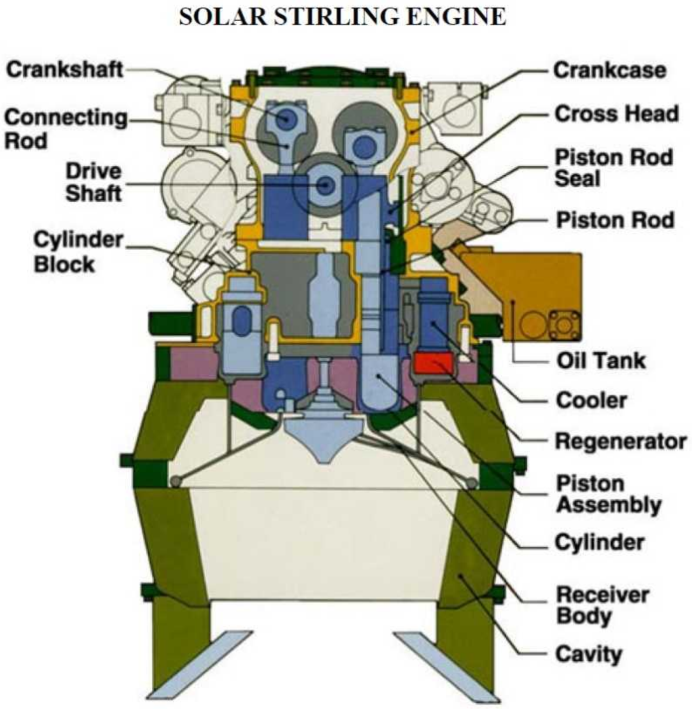
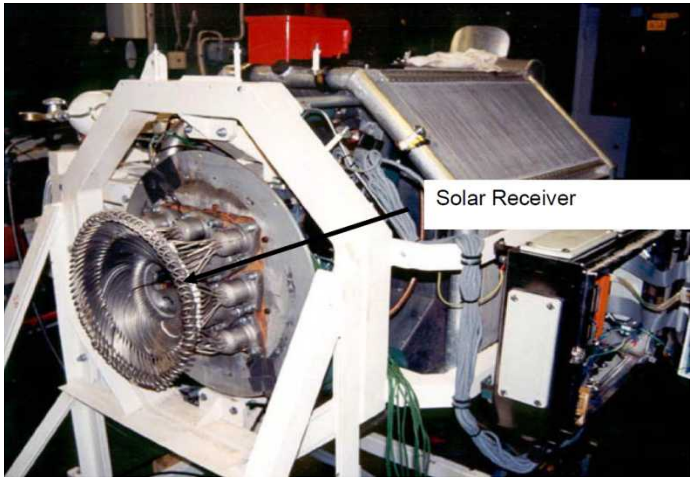


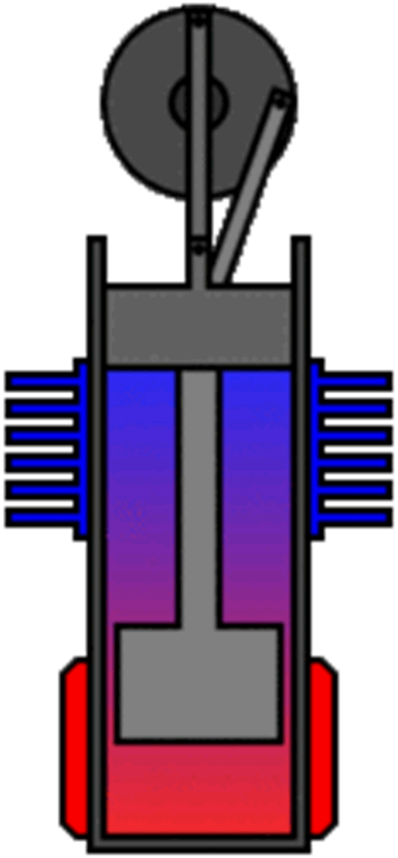

Illustration and photo of dish/engine system

(photo from http://en.wikipedia.org/wiki/Solar_thermal_energy)

# Dish/Engine – Stirling Cycle



www.energy.ca.gov

http://en.wikipedia.org/wiki/User:Zephyris

# CSP Commercial Plants

# Parabolic Trough Plants

http://en.wikipedia.org/wiki/SEGS


- Solar Electric Generating System (SEGS) Plant
  - 9 parabolic trough plants in Mojave Desert, CA (started in 1980's)
  - 354 MW installed capacity
- Nevada Solar One
  - Near Las Vegas, NV
  - 64 MW installed capacity
  - Commissioned ~2009
- Solana Generating Station
  - Gila Bend, AZ
  - 280 MW installed capacity

# eSolar Power Tower


5 MW in Lancaster, CA (started in 2009)
24,000 heliostats, two modules

# Ivanpah Solar Power Tower

## California (near Las Vegas, NV)

http://news.nationalgeographic.com


392 MWe direct-steam power tower plants in Ivanpah, CA. 170,000 heliostats. Opened February 2014

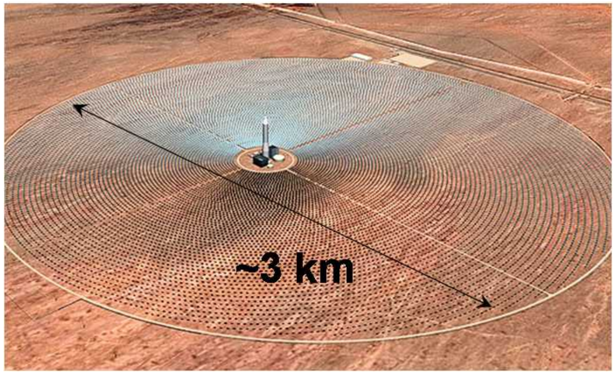
# Gemasolar

(near Seville, Spain)


- $1^{st}$ commercial power tower (19 MW) in the world with 24/7 dispatchable energy production (15 hours of thermal storage using molten salt). Commissioned in May 2011.

# Crescent Dunes

## Tonopah, Nevada




110 MWe molten-salt power tower under construction by SolarReserve near Tonopah, NV. Construction from 2011 – 2015.

# Khi Solar One

## Upington, South Africa

50 MWe steam power tower with 2 hours of steam storage. Tower is 205 m tall and has three cavity receivers.

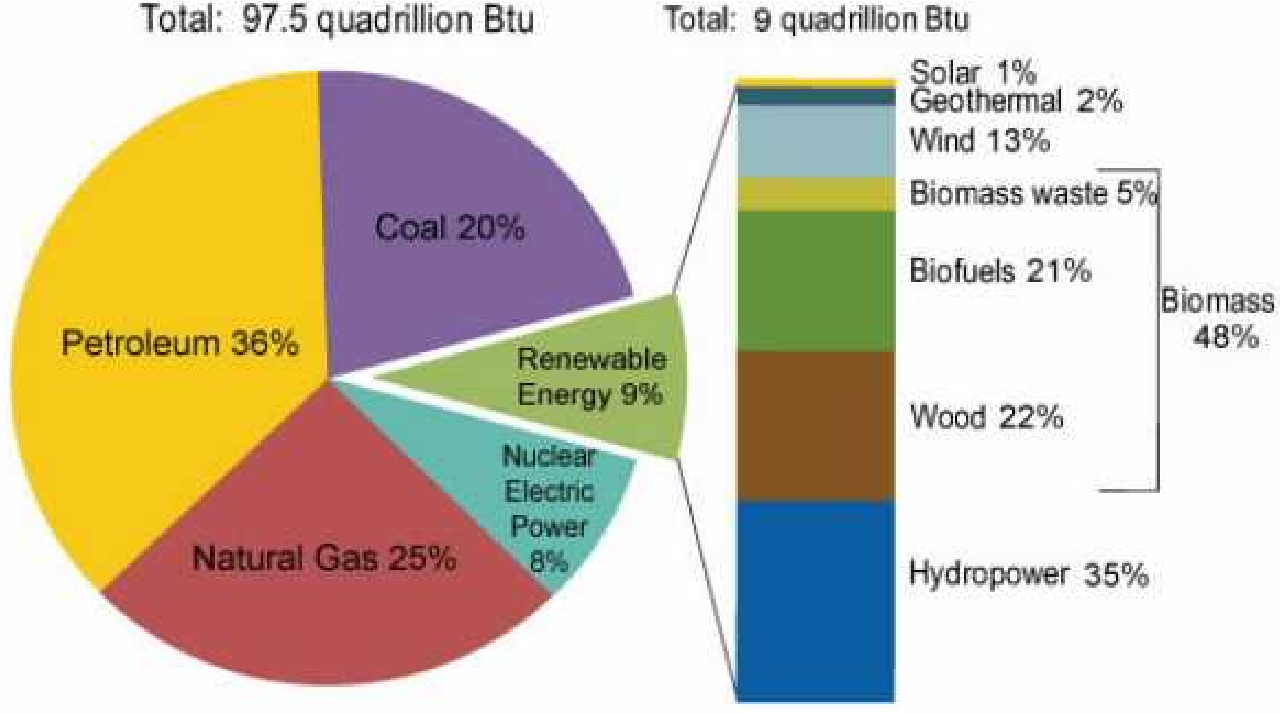
# Stirling Energy Systems Dish/Engine Plant

1.5 MW, 60 dishes near Phoenix, AZ (started in 2010; filed for bankruptcy in 2011)

# Outline

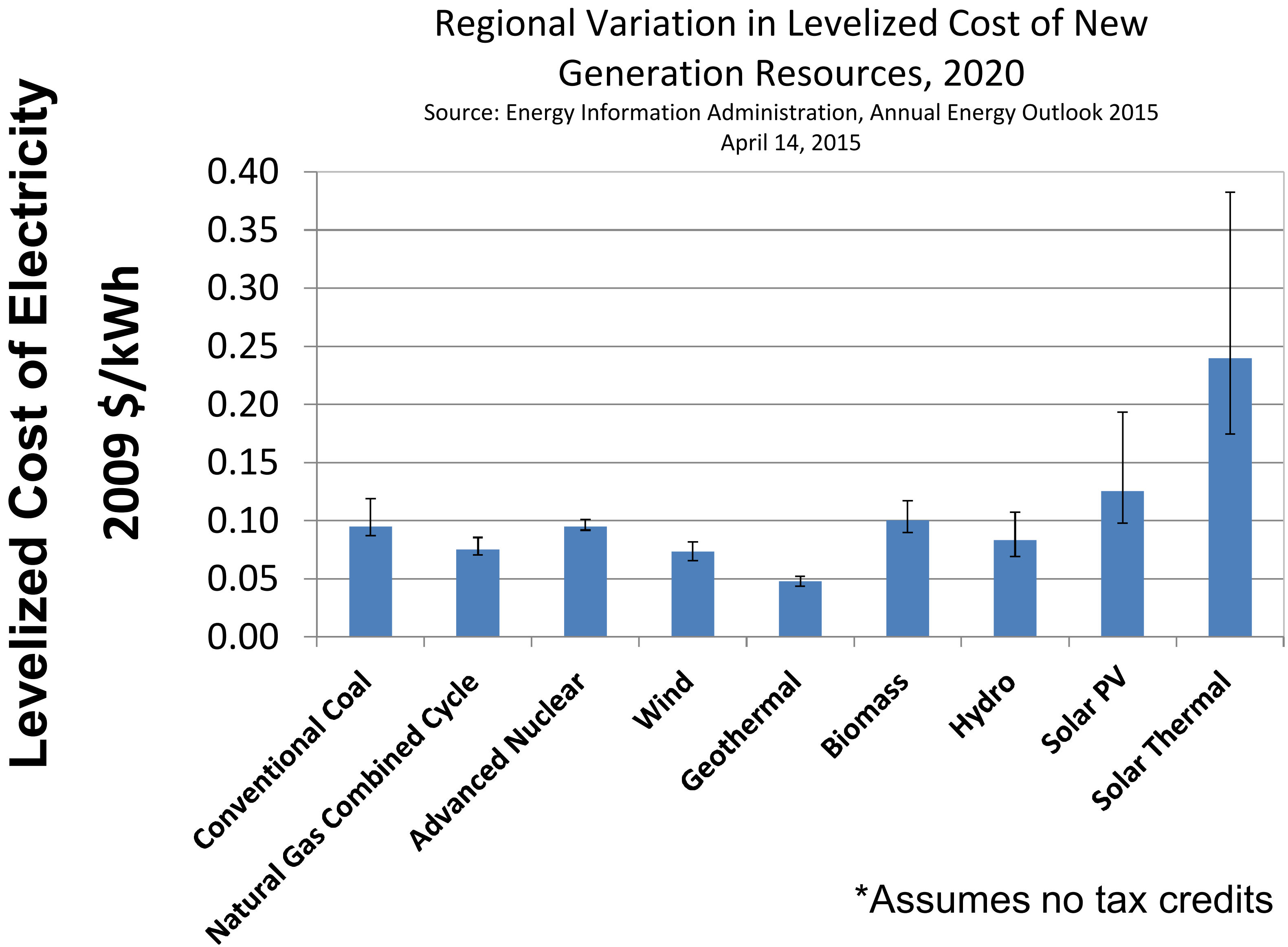
- **What is Concentrating Solar Power (CSP)?**
- **Economics of CSP**
- **CSP Research Needs**
- **Summary**

# U.S. Energy Consumption by Energy Source, 2011




Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 10.1 (March 2012), preliminary 2011 data.

# Electricity Costs (LCOE)*




*Assumes no tax credits

# DOE SunShot Goal

- **Reduce LCOE of solar-generated electricity to $0.06/kWh by 2020 with no tax credits**
  - Reduce cost of installed solar energy systems by 75%
  - Enable solar-generated power to account for 15–18% of America's electricity generation by 2030

SunShot
U.S. Department of Energy

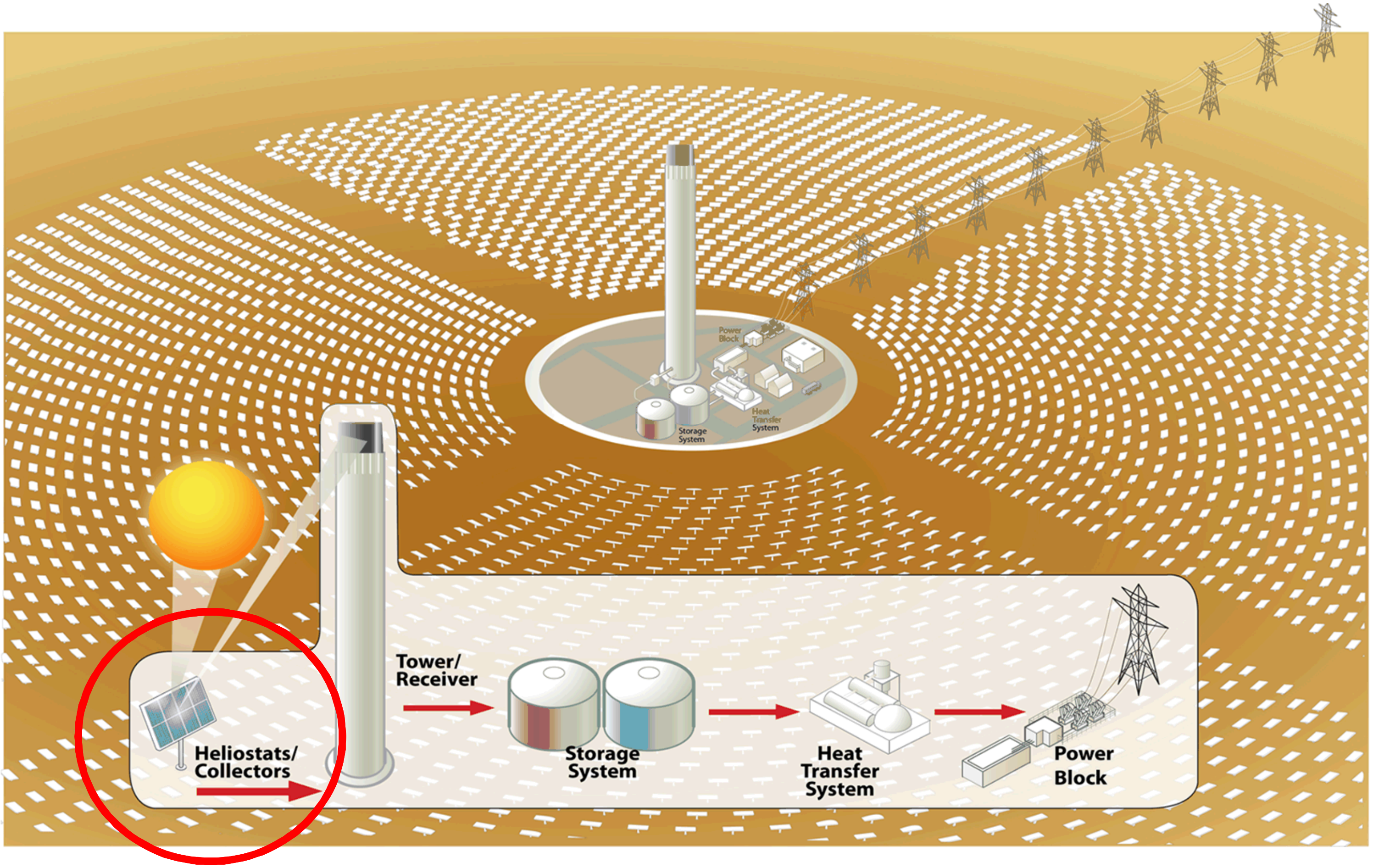
# Outline

- **What is Concentrating Solar Power (CSP)?**
- **Economics of CSP**
- **CSP Research Needs**
- **Summary and Review**

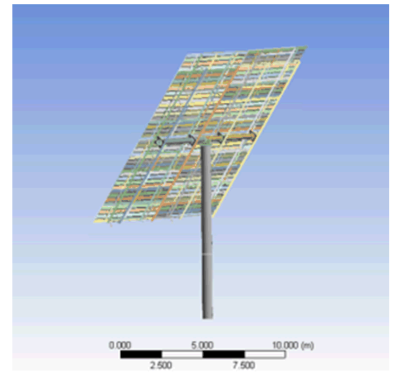
# Research Needs

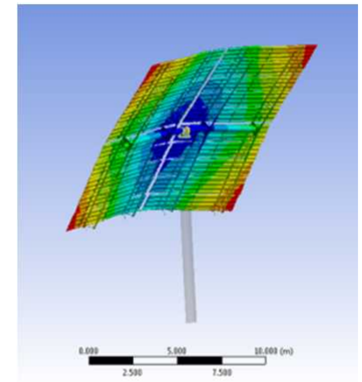
- Collectors (Mirrors) and Optical Performance
- High-Temperature Receivers
- Thermal Energy Storage

# Collectors and Optical Performance



# Optical Accuracy – Gravity Sag



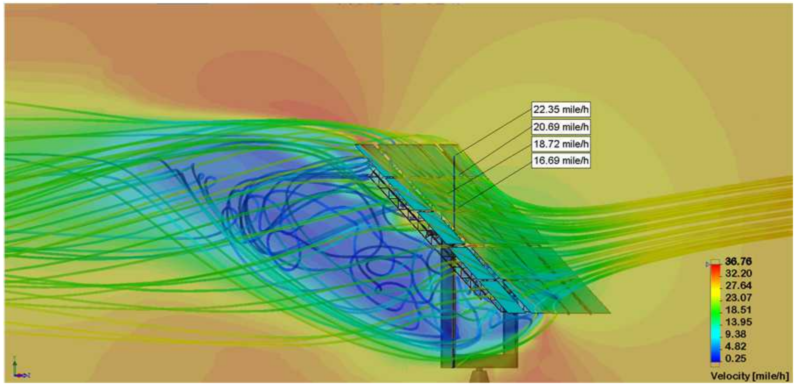



Mirror canting and gravity sag can affect optics
(J.Yuan)

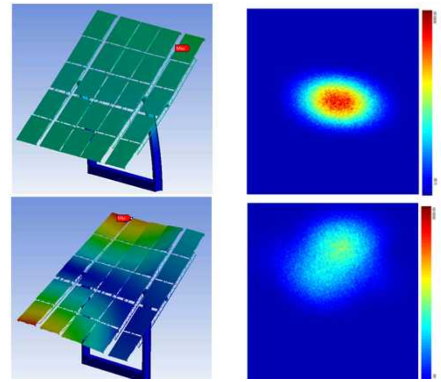
| Time | 10:03 AM | 12:30 PM | 3:12 PM | 4:12 PM | 5:45 PM |
|---|---|---|---|---|---|
| **Actual**<br>BCS Contour Plots |  |  |  |  |  |

- Need lightweight, stiff support structures (composite fibers, space frame?)

# Wind Impacts – Optics and Fatigue

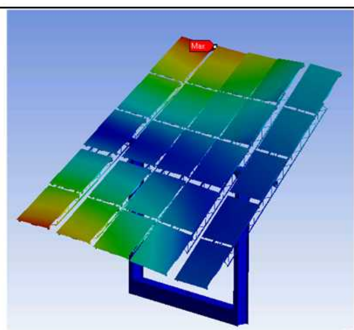
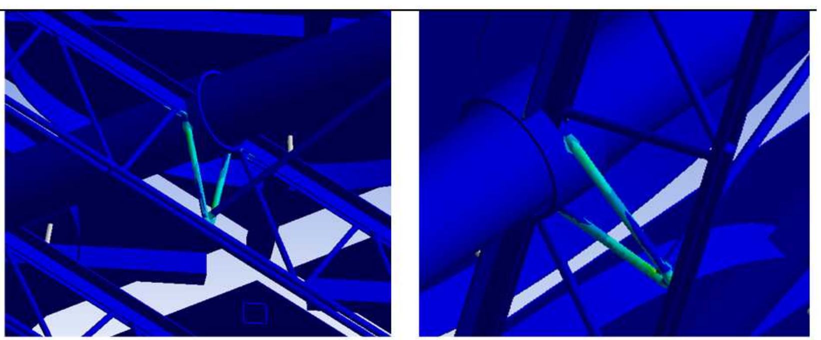


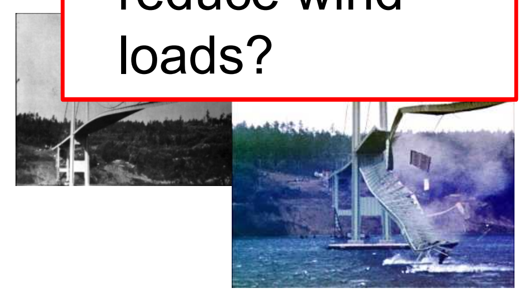

J. Sment, J. Christian, J. Yuan



Optics impacted by "sway" or out-of-plane bending

- Need dampeners or anti-vibration devices
- "Winglets" to reduce wind loads?

| Mode shape | Fatigue Affected Areas |
|---|---|
|  Mode 2 |  Truss Cross Members at Torque Tube |

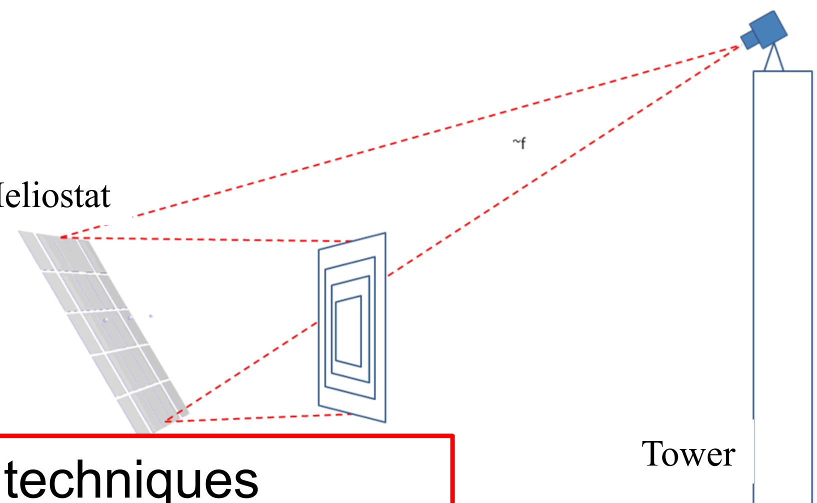


Tacoma Narrows Bridge collapsing under 40 mph winds (1940)

# Optical Accuracy – Characterization, Alignment, and Tracking

(Andraka, Yellowhair, Smith)

Sandia National Laboratories

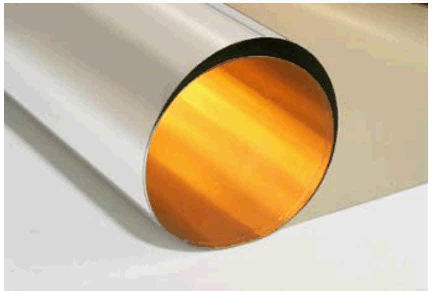



- Need smart alignment techniques
- MEMS-based self adjusting surfaces?
- Novel tracking methods

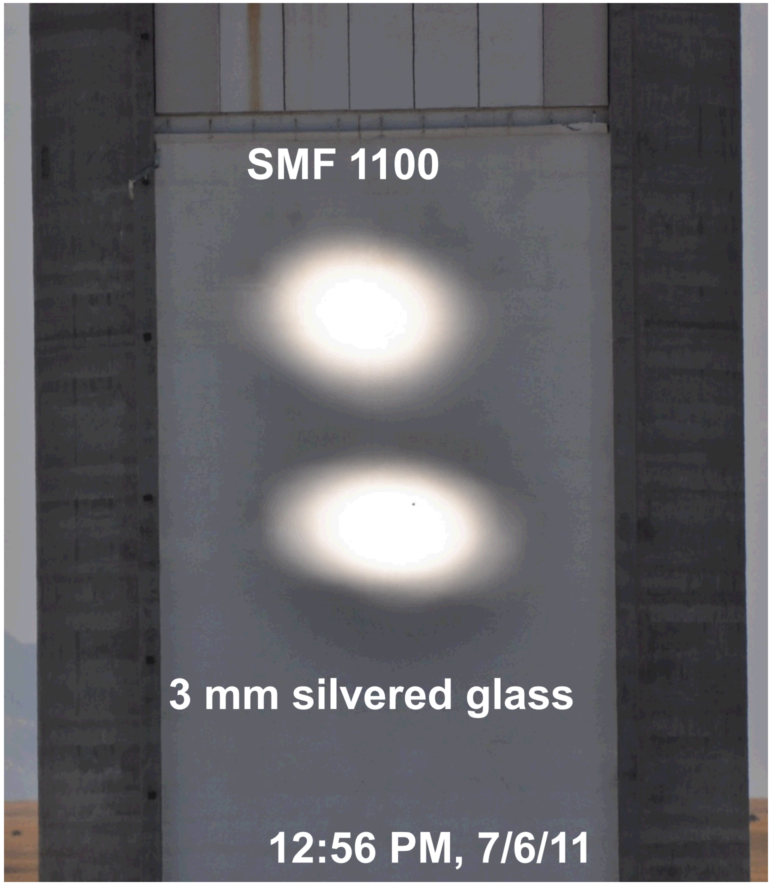
Before

After

# Advanced Reflective Materials



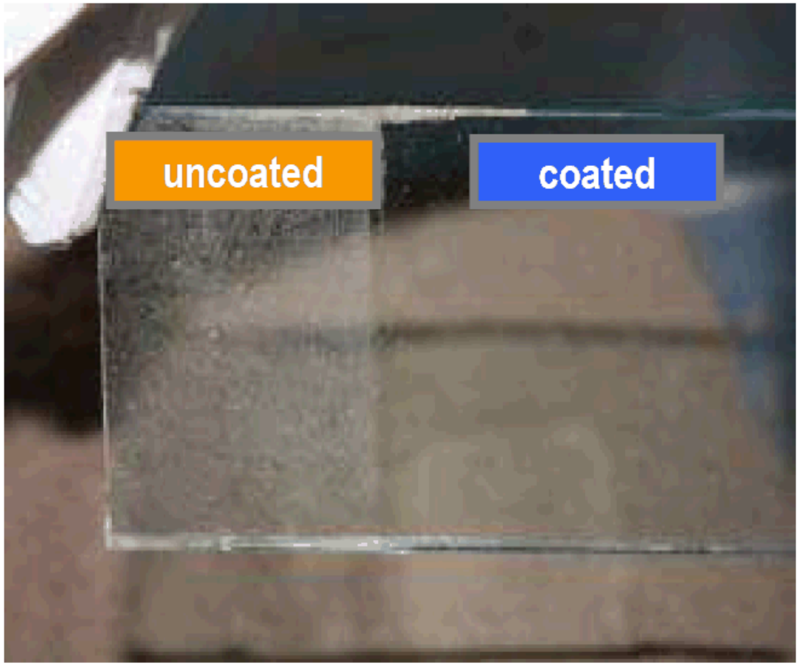
Heliostat with 3M™ Solar Mirror Film 1100



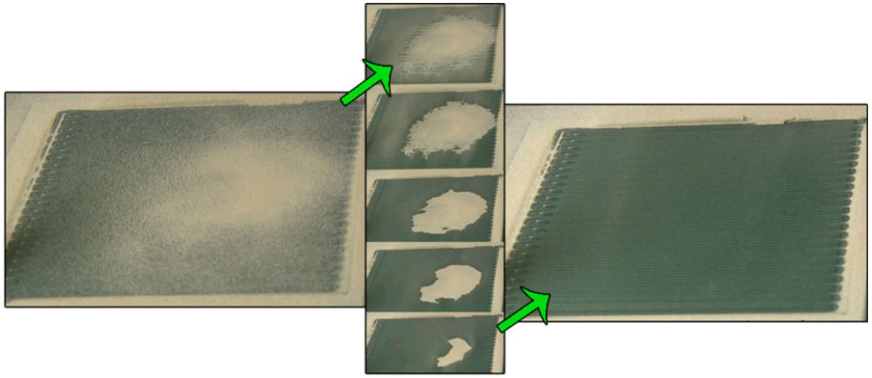
# Anti-Soiling Coatings

- Need anti-soiling coatings for mirrors to reduce need for washing and maintain high reflectivity


# Anti-Soiling Coatings and Devices

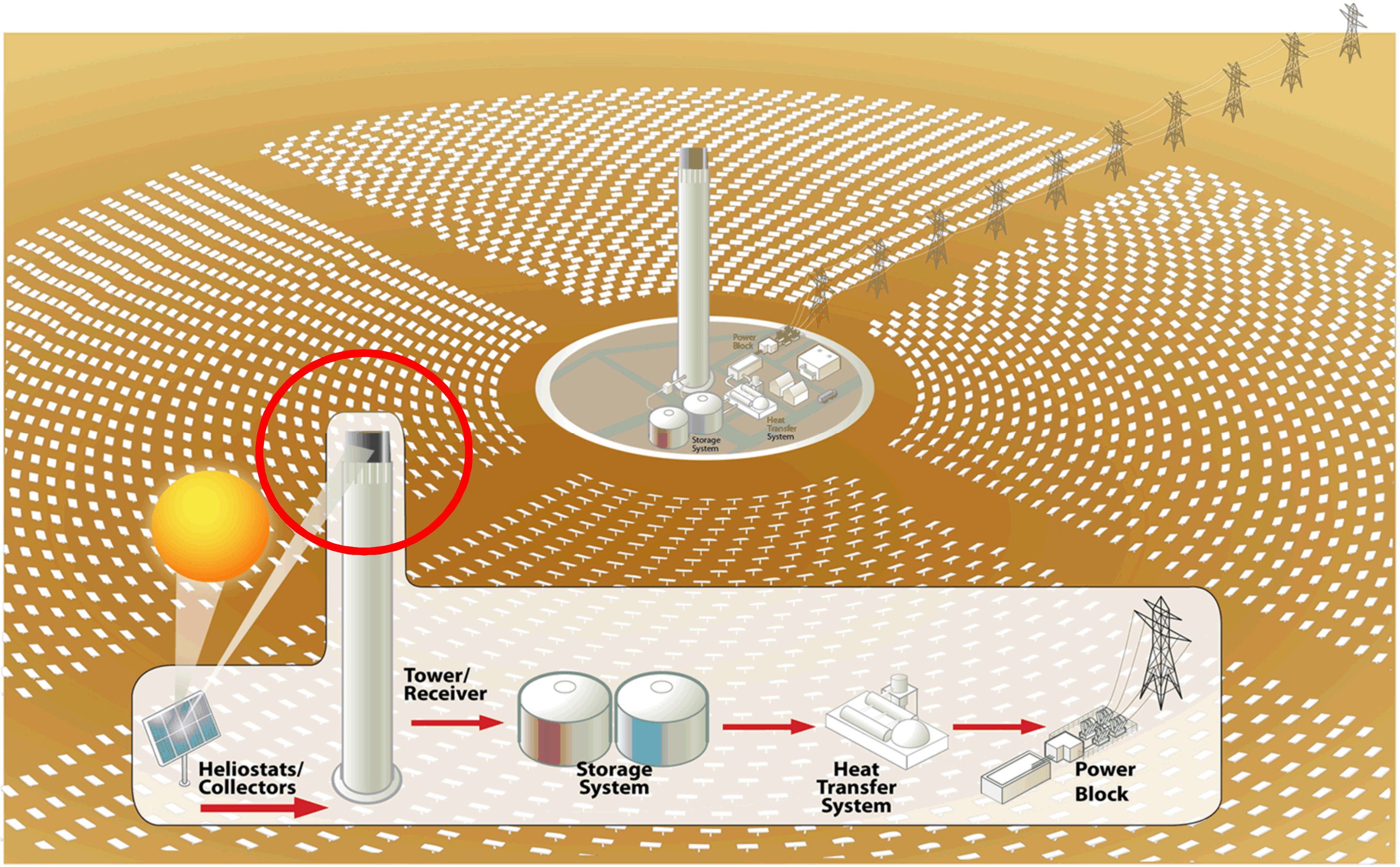



3M Anti-Soiling Coating
(nanoparticle based liquid pH ~3)



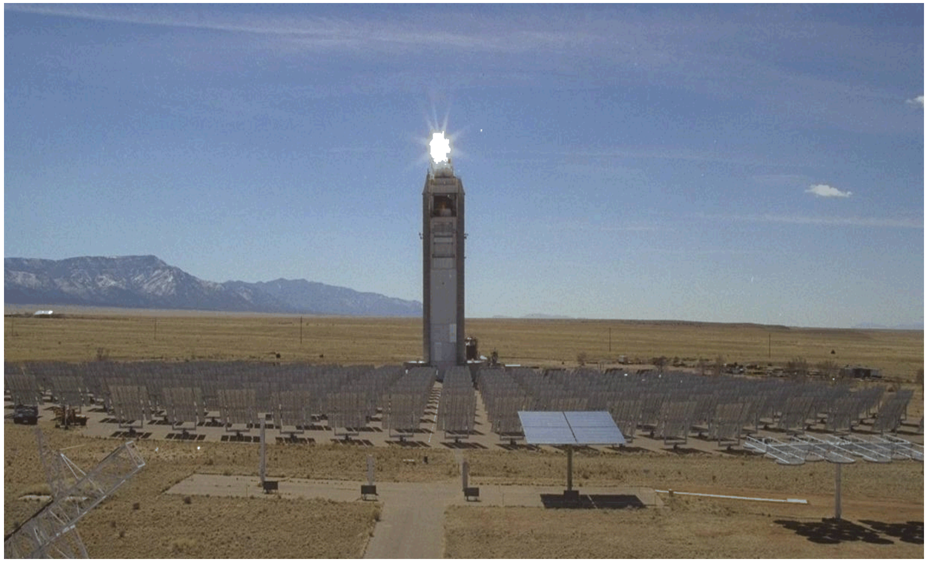
M. Mazumdar (Boston University)
Electrodynamic screens charge particles and lift them off the surface

# Receivers



Power Block
Storage System
Heat Transfer System
Tower/ Receiver
Heliostats/ Collectors
Storage System
Heat Transfer System
Power Block

# High-Temperature Receivers



National Solar Thermal Test Facility, Sandia National Laboratories, Albuquerque, NM

Cavity receiver

External tubular receiver

- Maximize solar absorptance and minimize heat loss (selective absorber coatings, geometry, concentration ratio)
- Need materials that operate at high temperature (>650 °C) and are durable in air

# Fractal-Like Receiver Designs

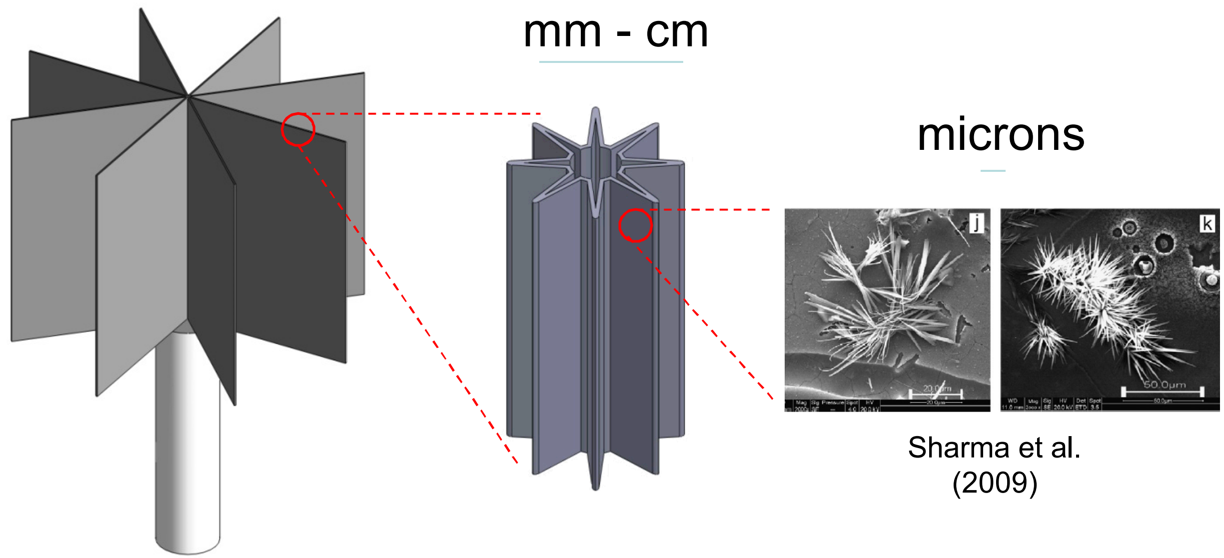


- Develop fractal-like designs and structures across multiple scales to increase solar absorptance while minimizing heat loss

~10 m

Conventional cylindrical solar receiver

meters

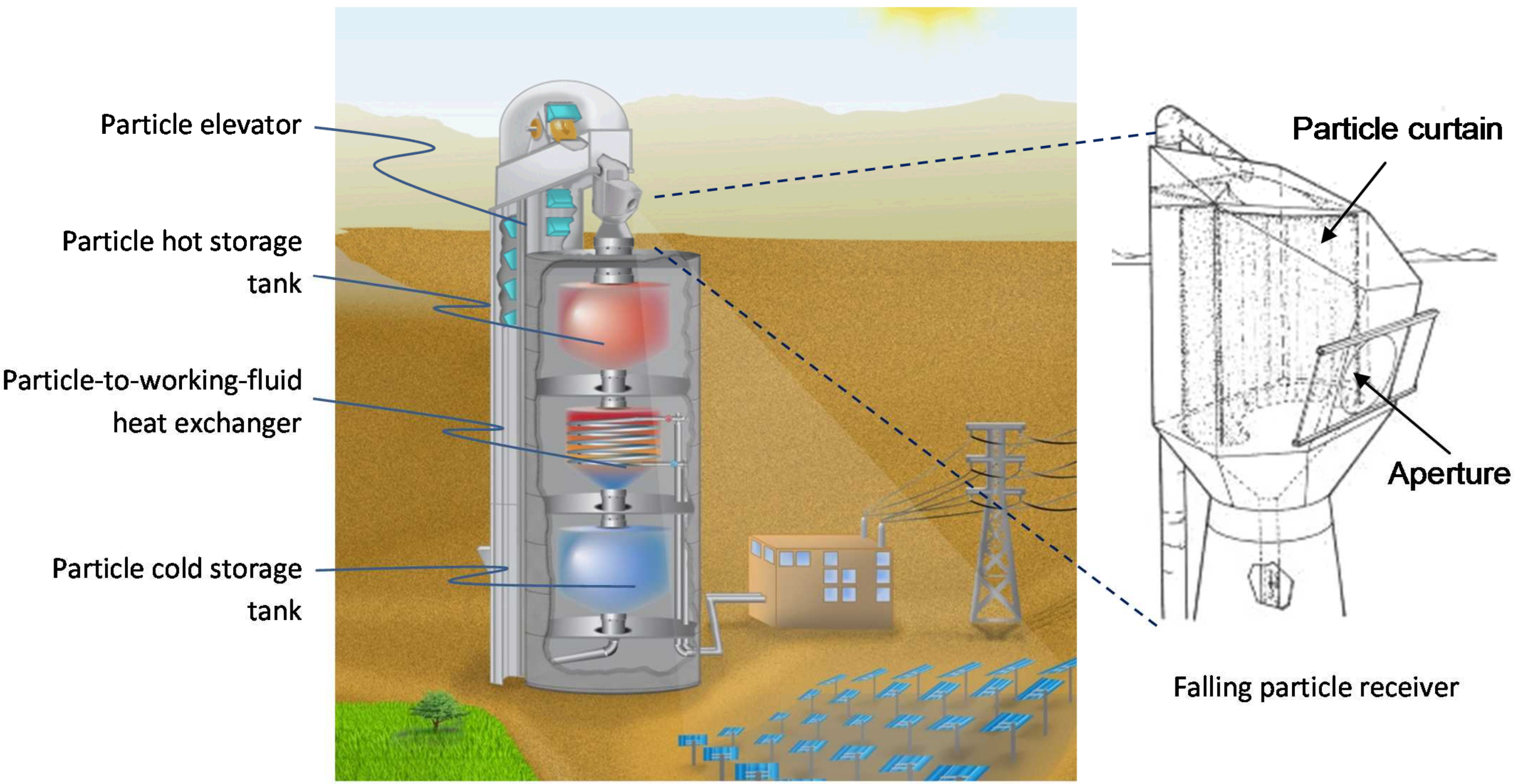



Sharma et al. (2009)

New fractal-like designs with light-trapping and low-emittance properties at multiple scales

**Patents Pending**

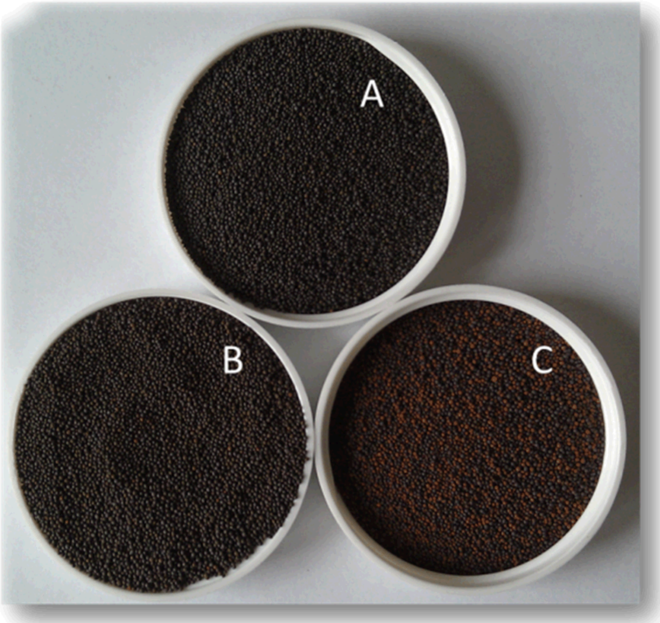
# High Temperature Falling Particle Receiver (DOE SunShot Award FY13 – FY15)




Participants: Sandia, Georgia Tech, Bucknell U., King Saud Univ., DLR

# Advantages of Particle Receivers

- Direct heating of particles
  - Higher temperatures than conventional molten salts
    - Enable more efficient power cycles (e.g., $sCO_2$ at ~700 C)
  - Higher solar fluxes for increased receiver efficiency
- Direct storage of hot particles
  - Reduced costs




CARBO ceramic particles (“proppants”)

# General Approach

**Phase 1**

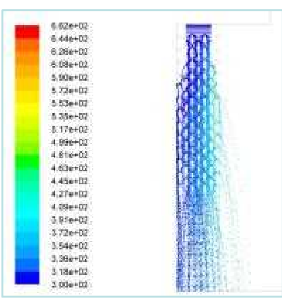
- Modeling, design, proof-of-concept testing

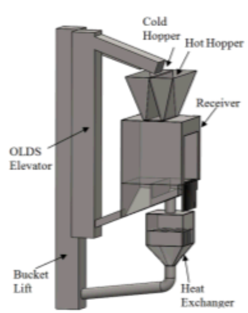
**Phase 2**

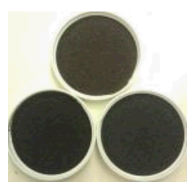
- Component testing, model validation, design optimization

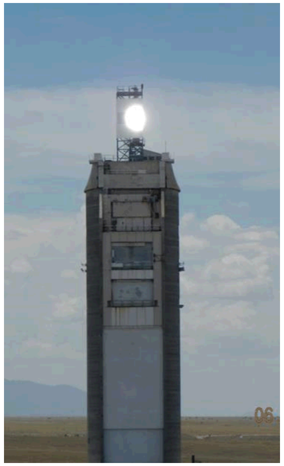
**Phase 3**

- Prototype development for on-sun testing

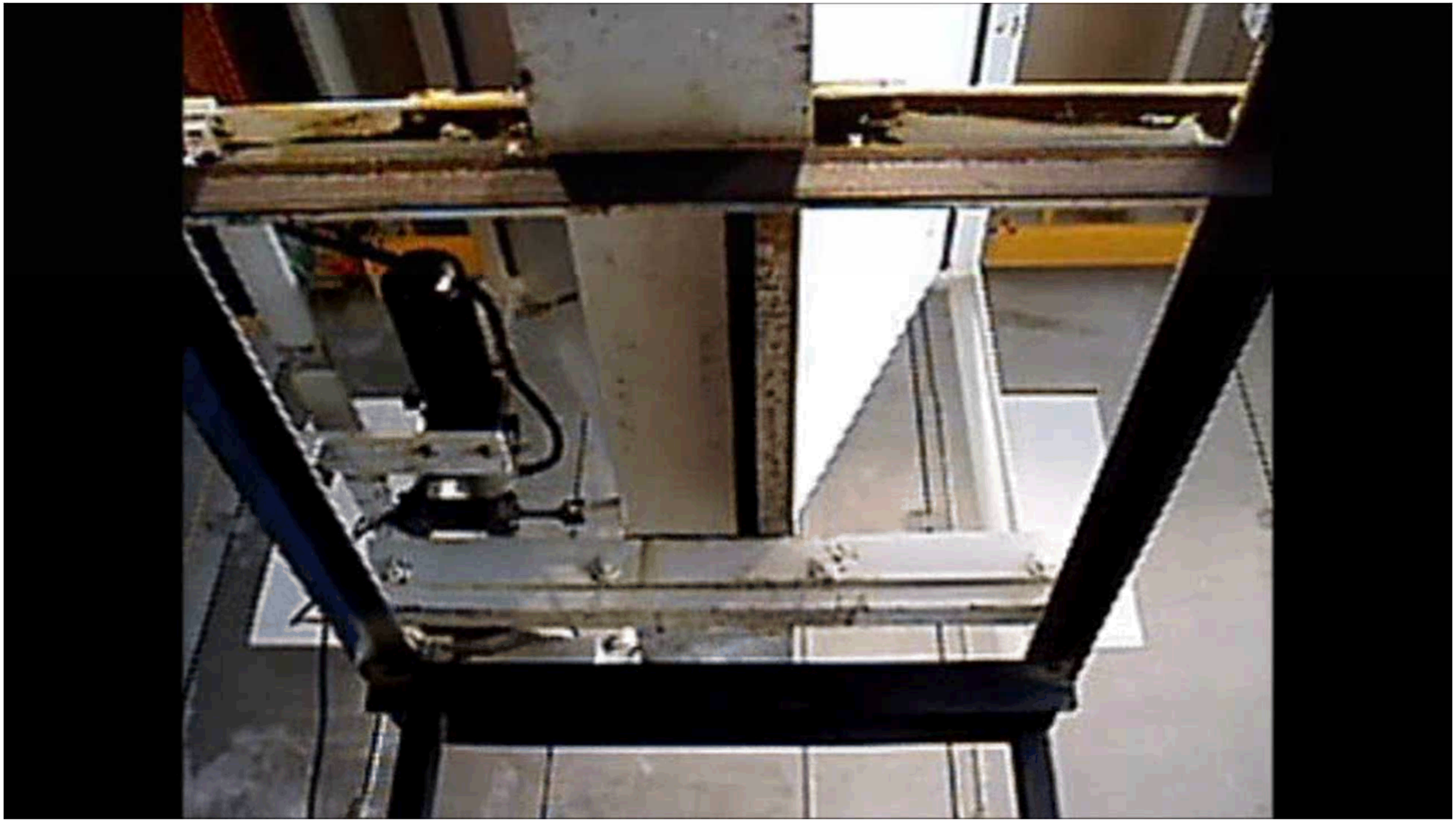




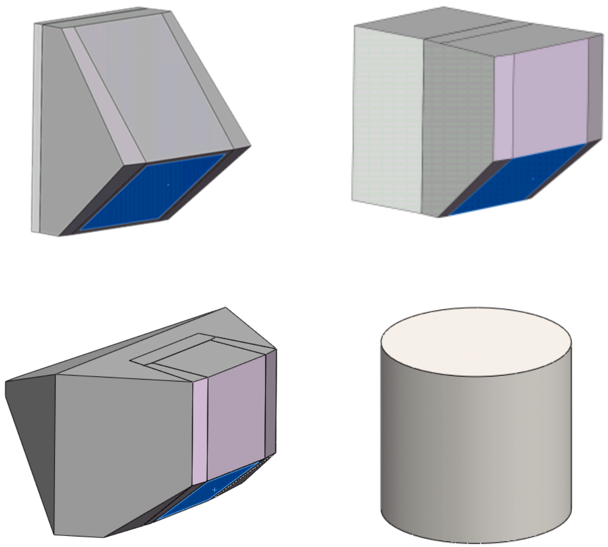





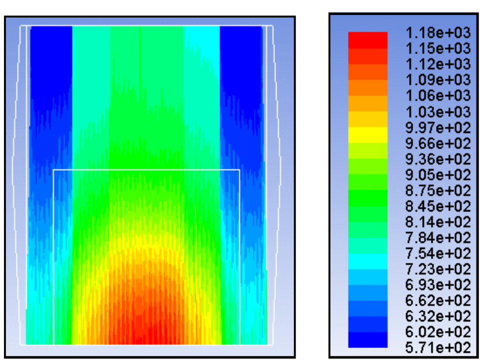
# Particle Receiver Designs – Free Falling

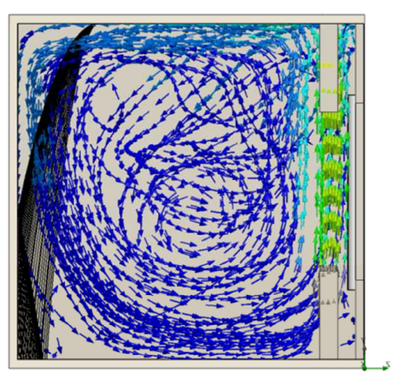


# Free-Falling Receiver Designs

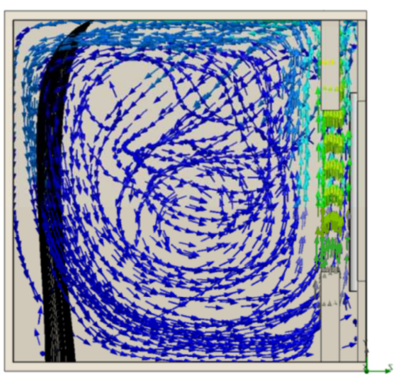


- Developed CFD models to optimize receiver performance
  - ANSYS FLUENT: Radiation, convection, discrete phase particles, turbulence
  - Features modeled
    - Alternative geometries
    - Particle recirculation
    - Air curtain
    - Particle size, mass flow rate, release patterns

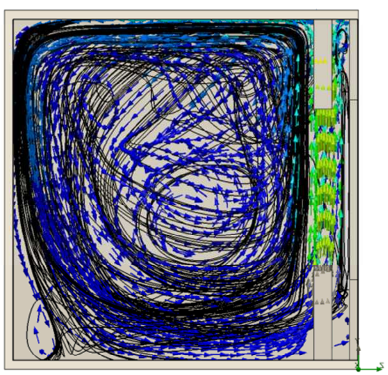


1 mm particle size

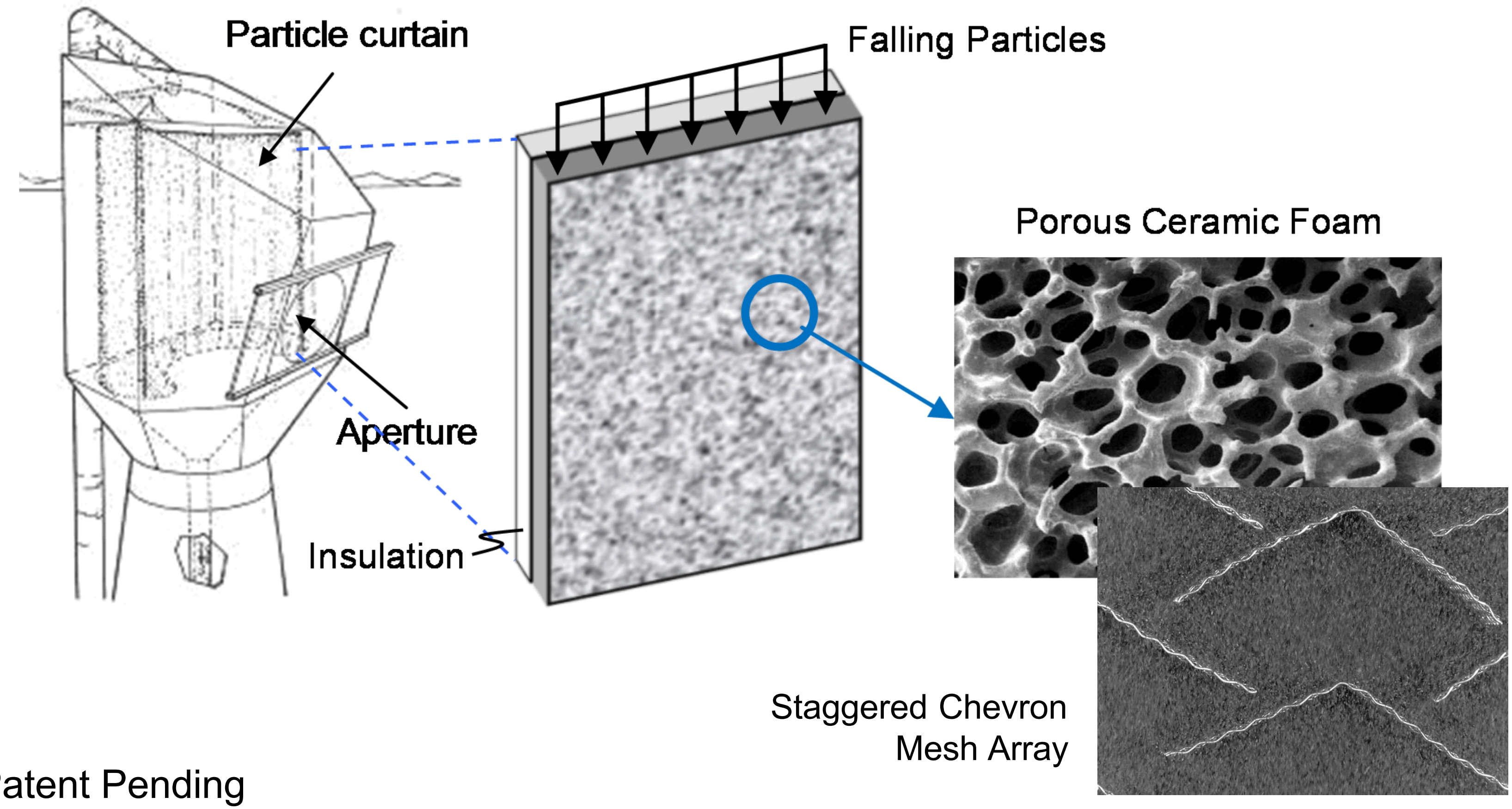


100 μm particle size



10 μm particle size

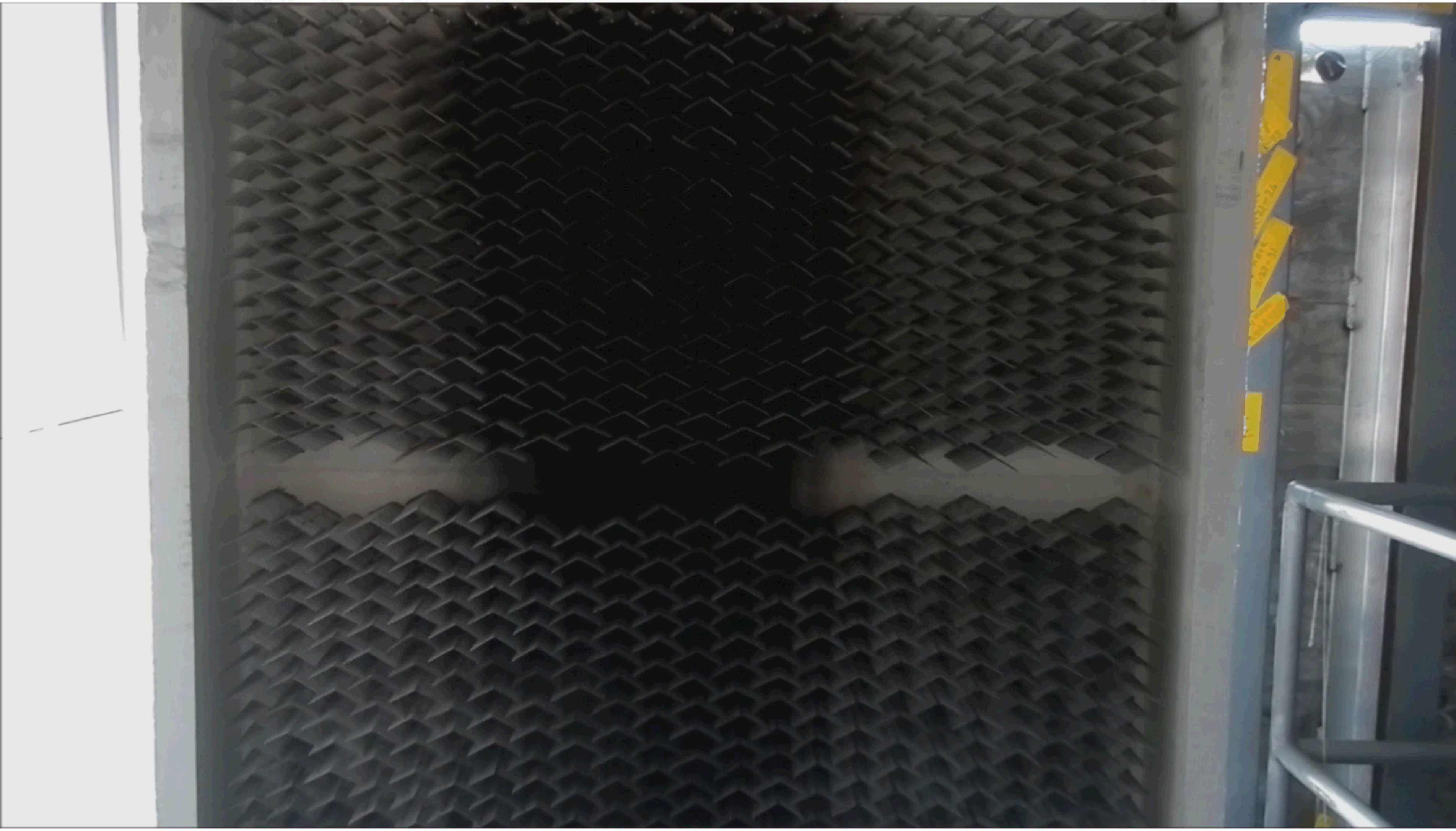
# Obstructed Flow Designs



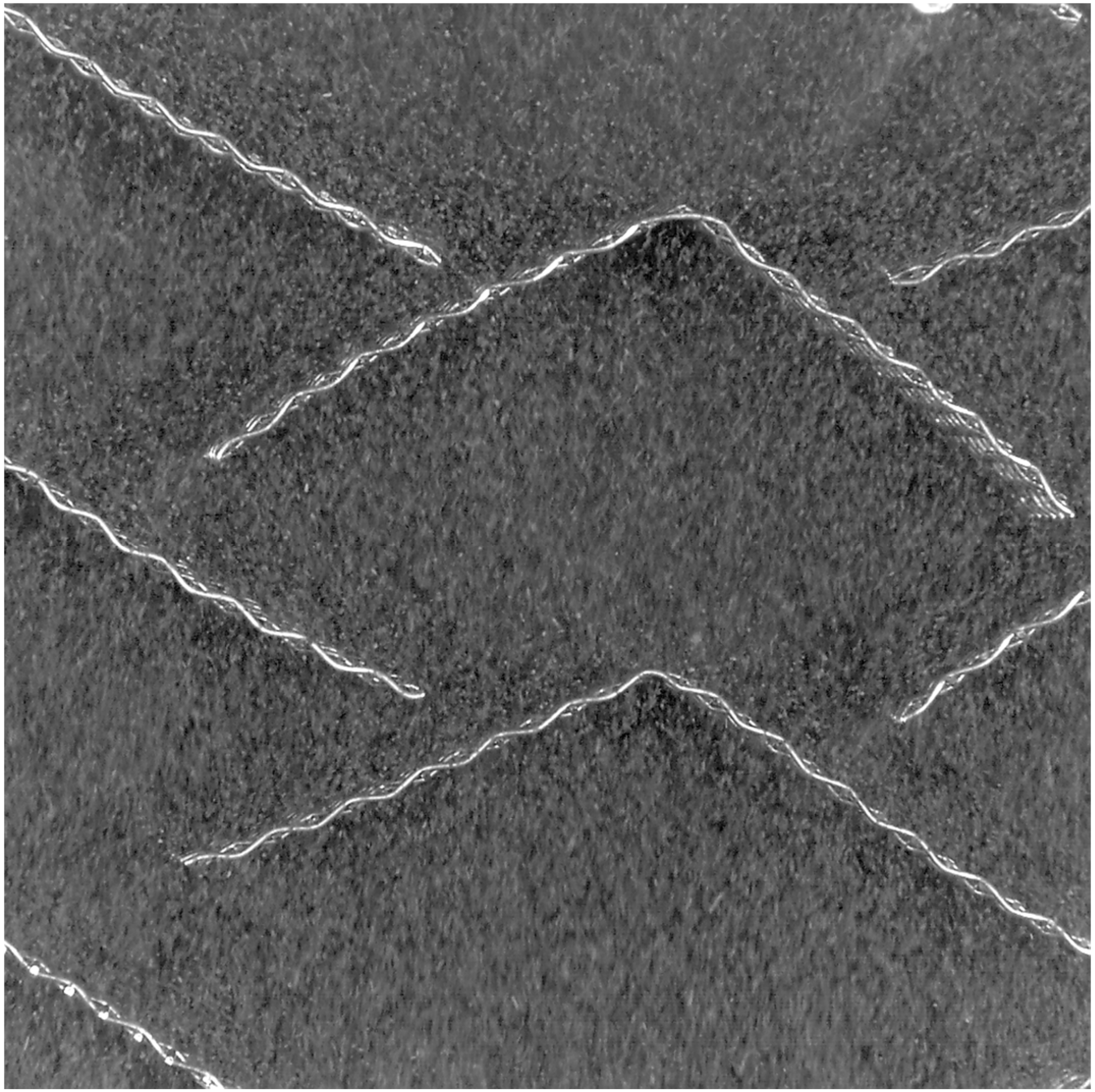

Patent Pending

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



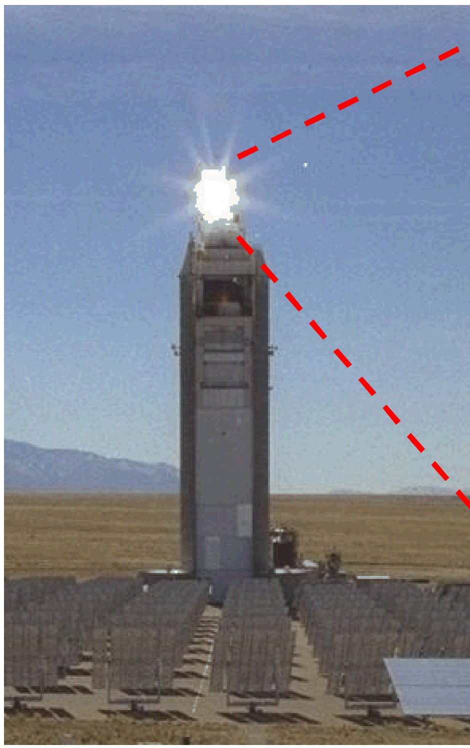
# Particle Flow over Chevron Meshes

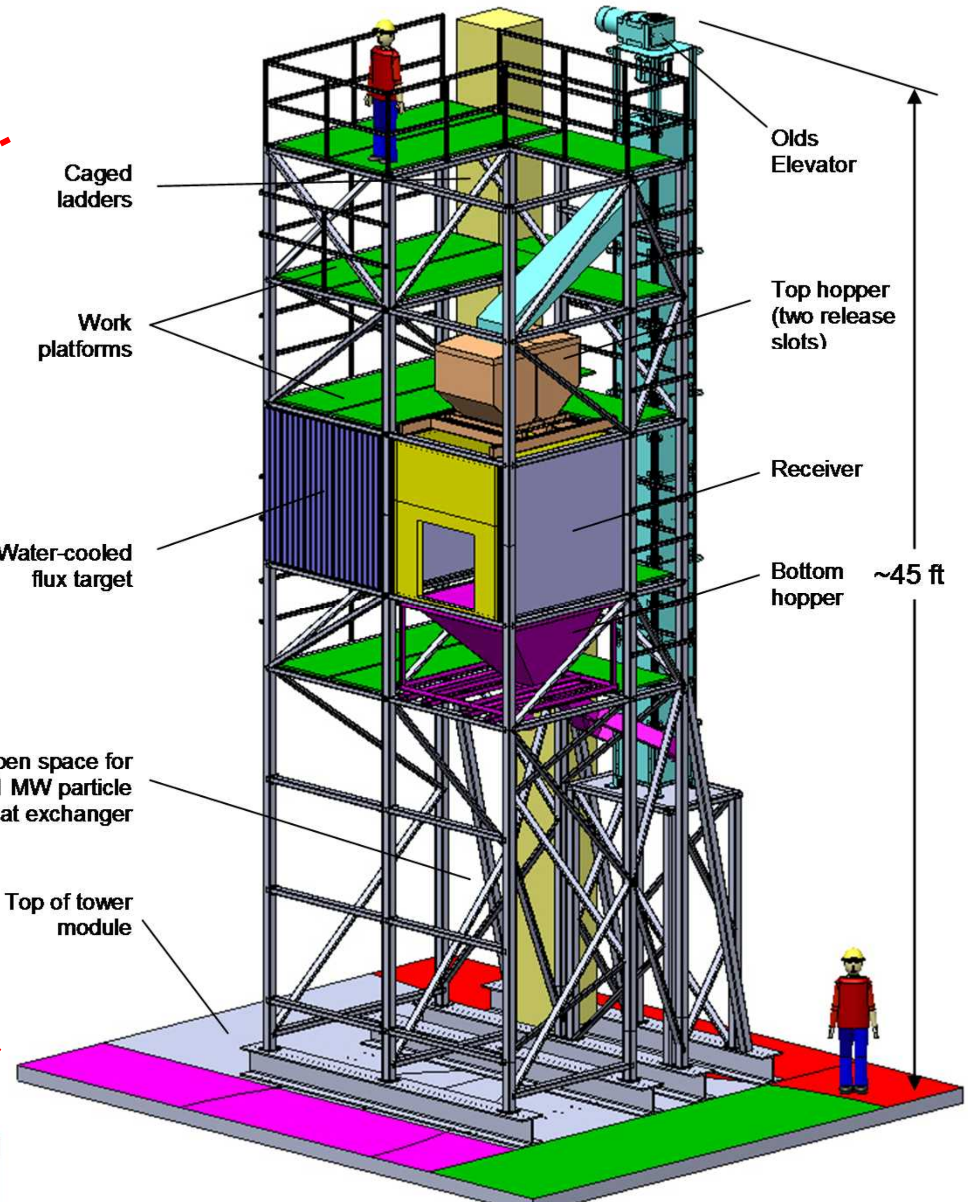


**Pros**: particle velocity reduced for increased residence time and heating

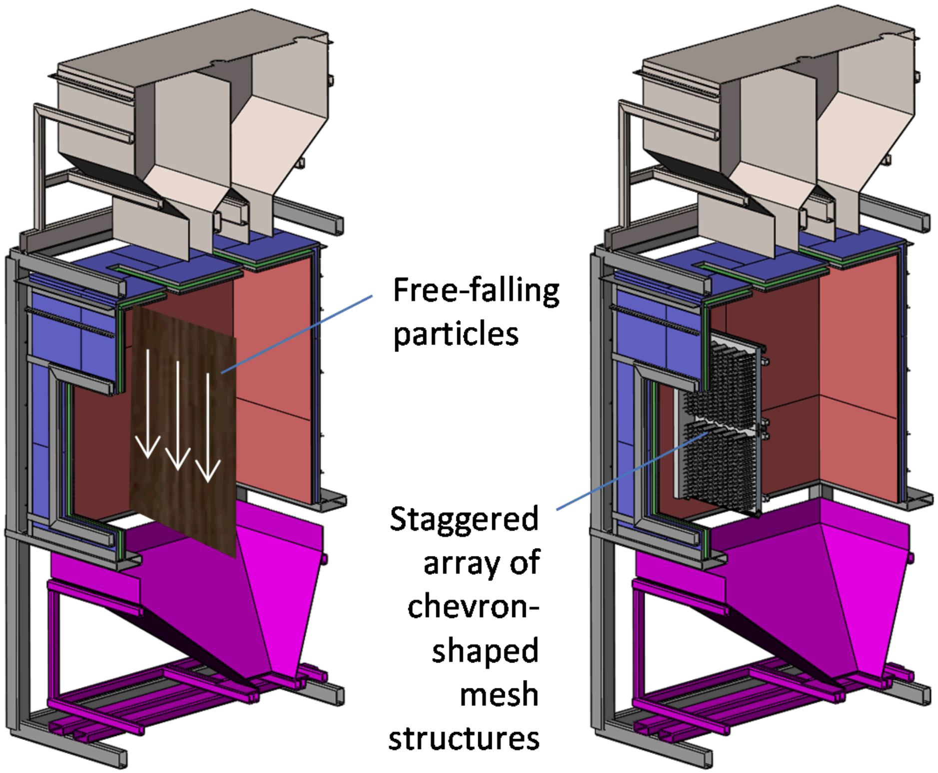
**Cons**: Mesh structures exposed to concentrated sunlight (~1000 suns)

# Prototype System Design





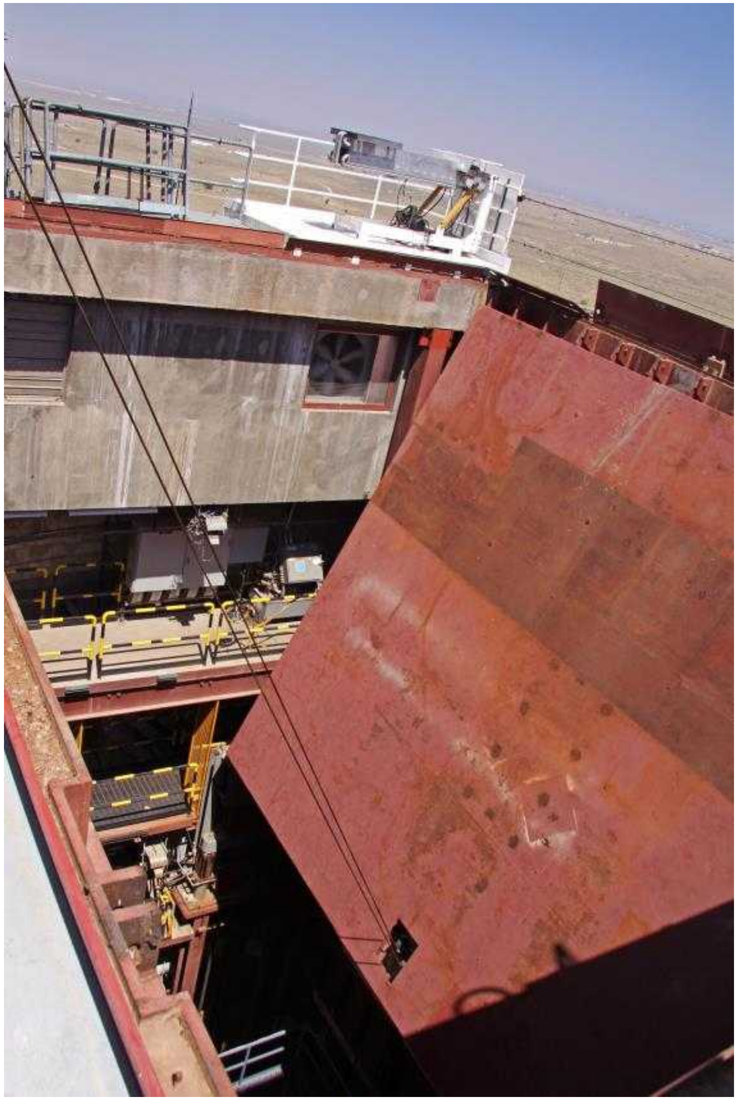
# Particle Release Configurations




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

# Lifting the system to the top of the tower

Sandia National Laboratories



# Lifting the system to the top of the tower

Sandia National Laboratories

# On-Sun Tower Testing

# On-Sun Tower Testing


Over 300 suns on receiver
(June 25, 2015)

# On-Sun Tower Testing

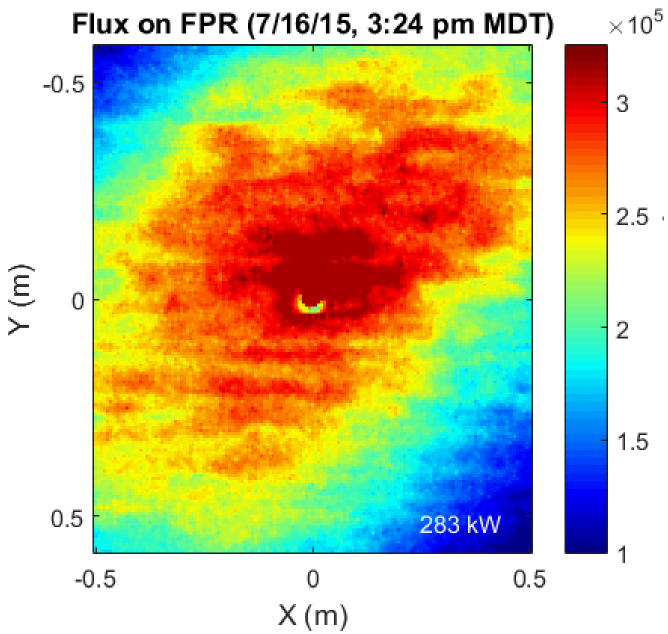
Over 600 suns peak flux on receiver
(July 20, 2015)

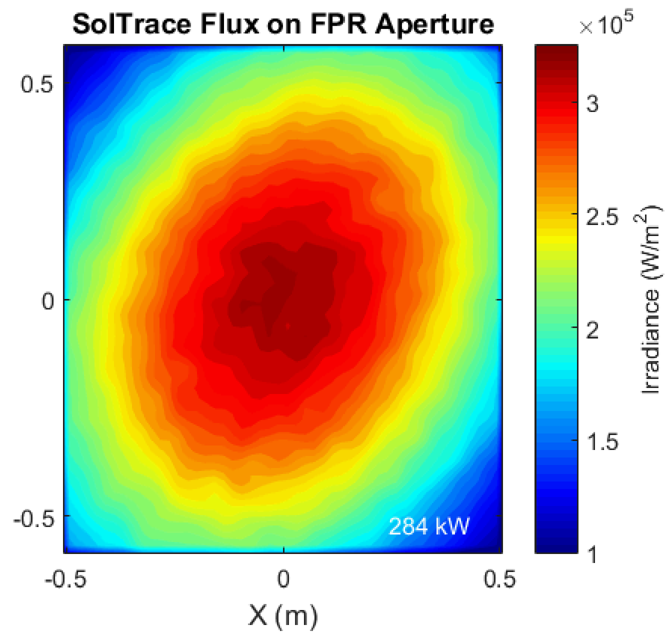
# On-Sun Tower Testing

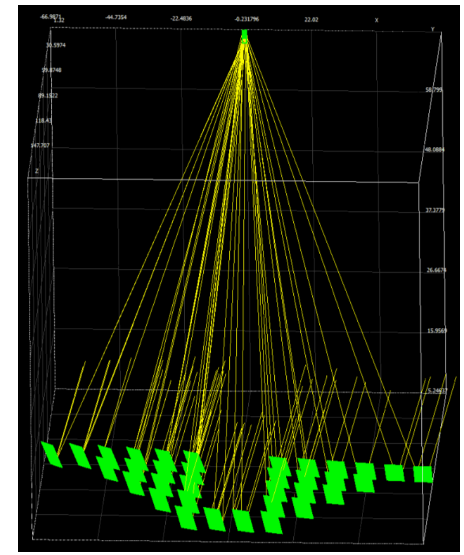
Particle Flow Through Mesh Structures
(June 25, 2015)

# Irradiance Measurements

Sandia National Laboratories



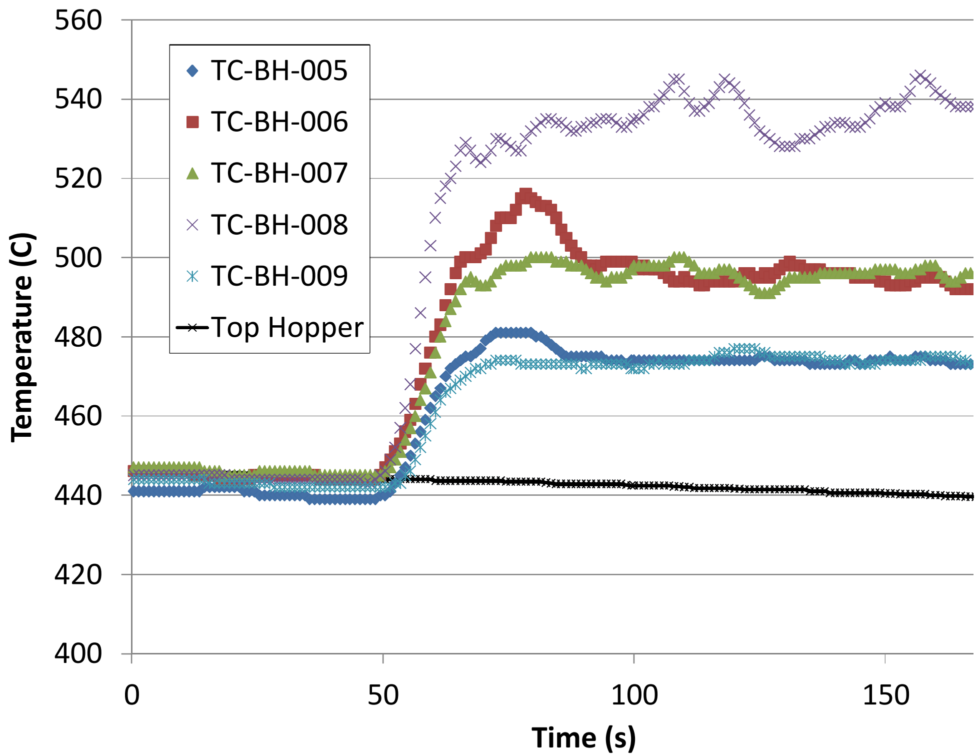



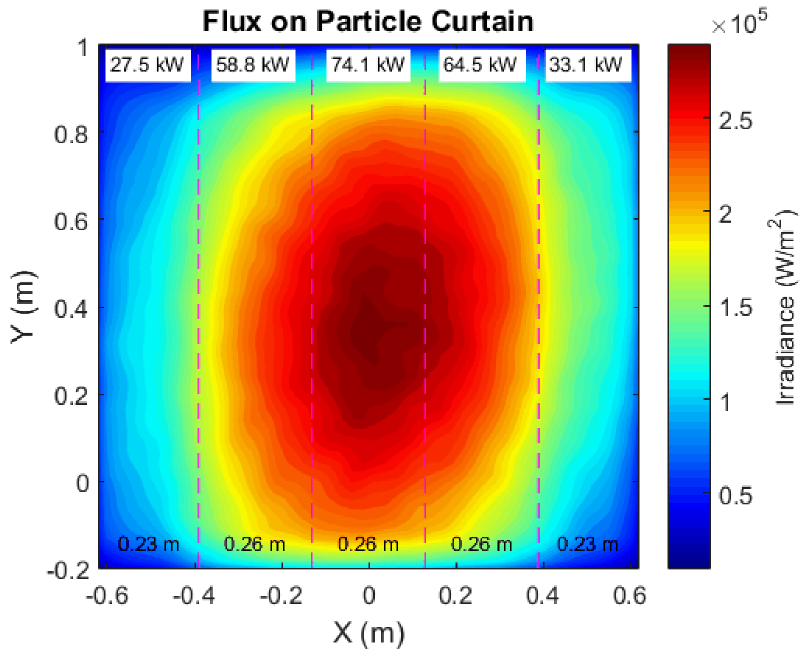



**Measured**

**Simulated using Ray Tracing (SolTrace)**

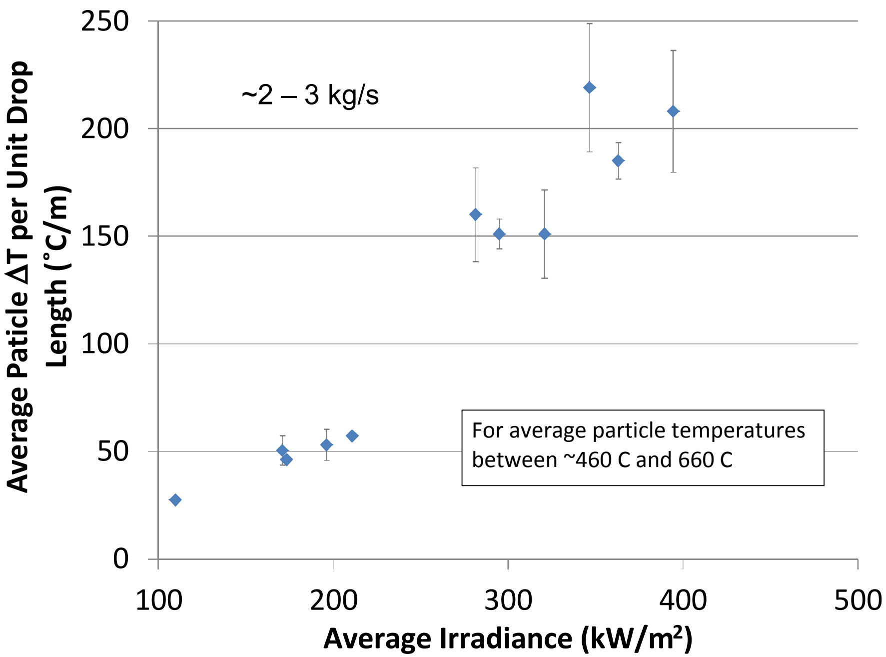
# Temperature Measurements



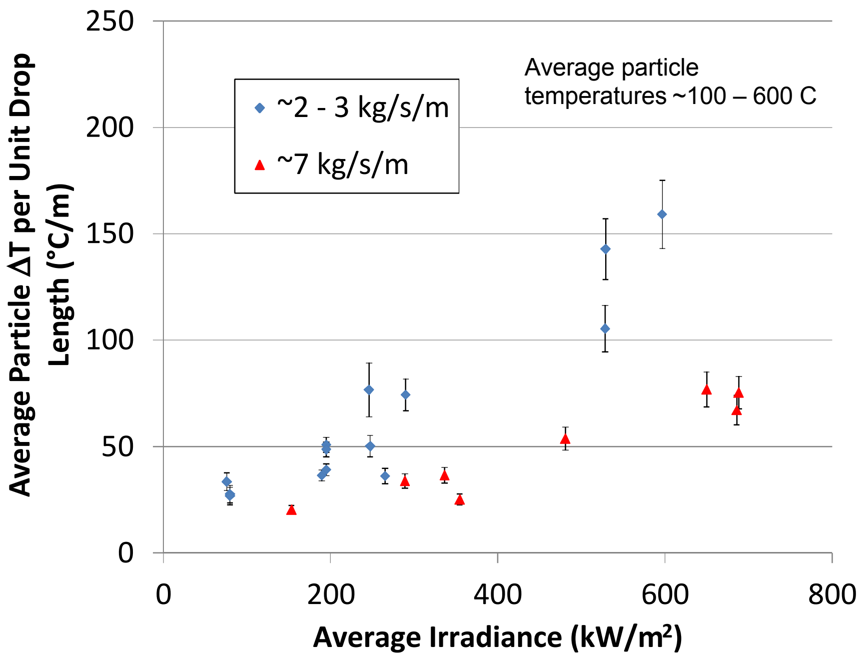



# Particle Temperature Rise

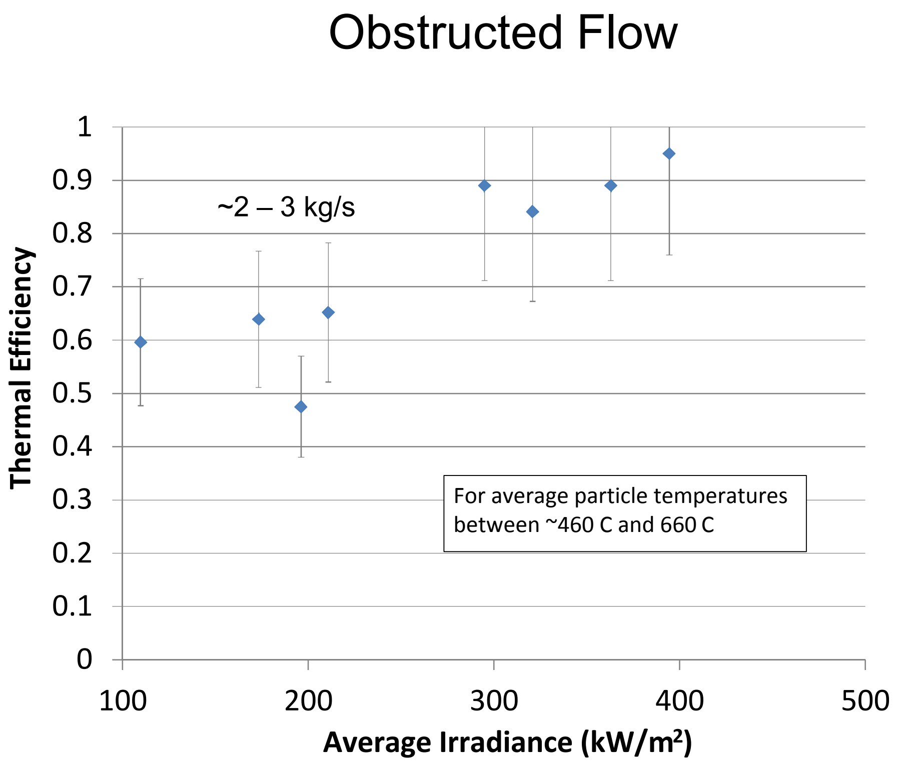
## Obstructed Flow

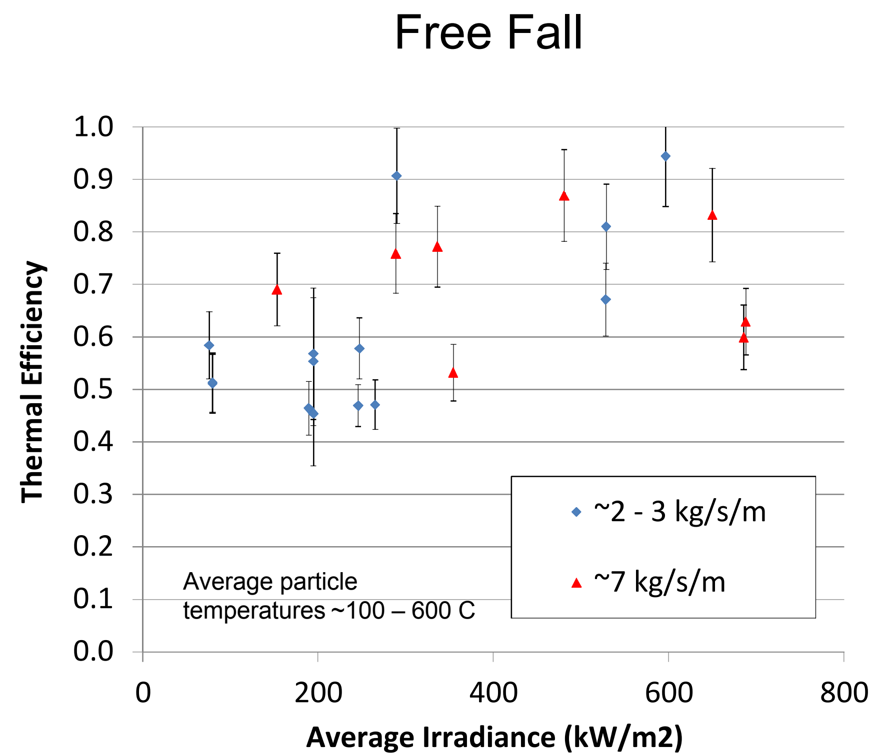



## Free Fall



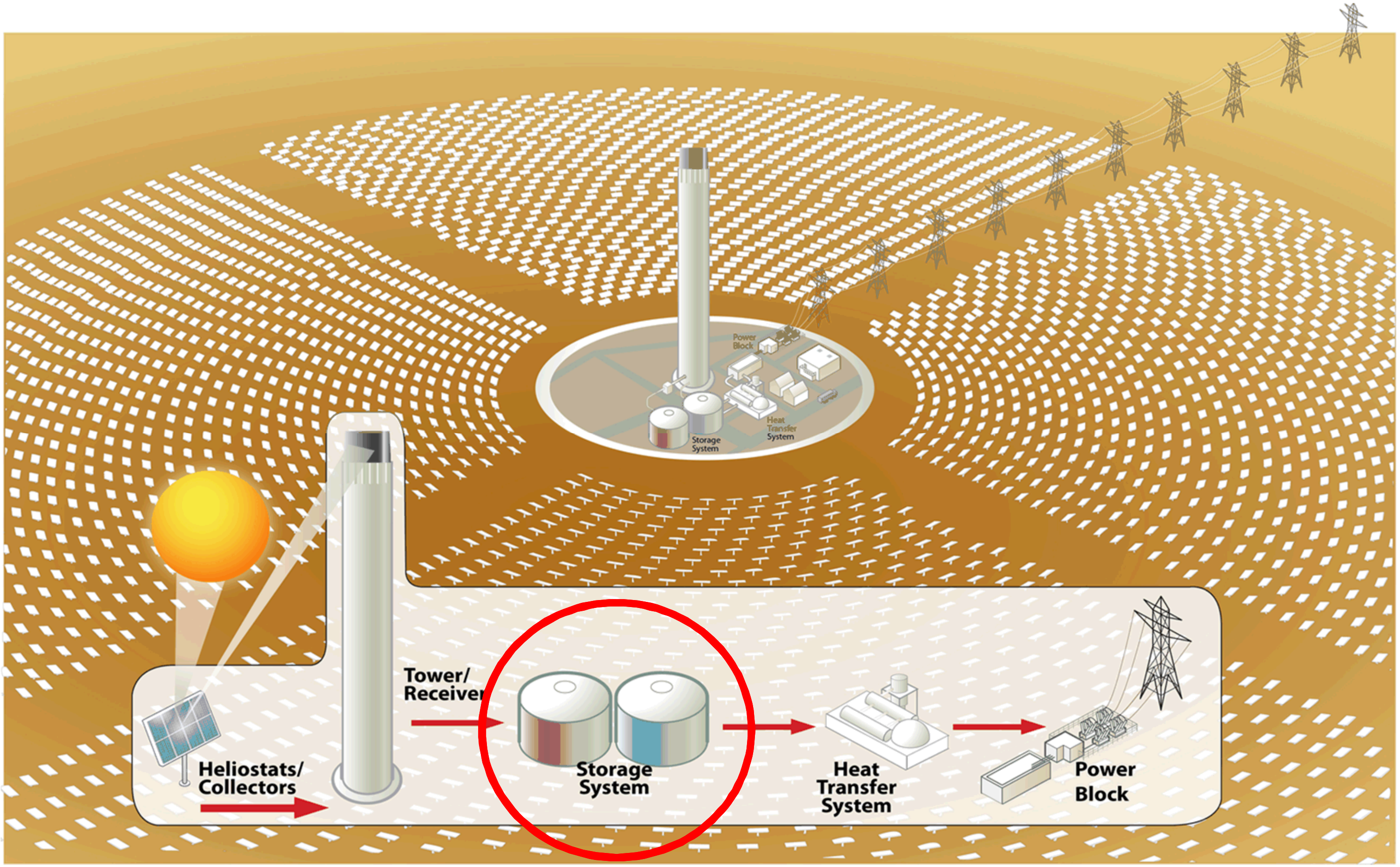
# Thermal Efficiency




$$\eta_{th} = \frac{Q_{abs}}{Q_{in}} = \frac{\dot{m}\left(h_{out} - h_{in}\right)}{Q_{in}} = \frac{\dot{m}\int_{T_{in}}^{T_{out}} c_p\left(T\right)dT}{Q_{in}} = \frac{\dot{m}\left[\frac{365}{1.18}\left(T_{out}^{1.18} - T_{in}^{1.18}\right)\right]}{Q_{in}}$$

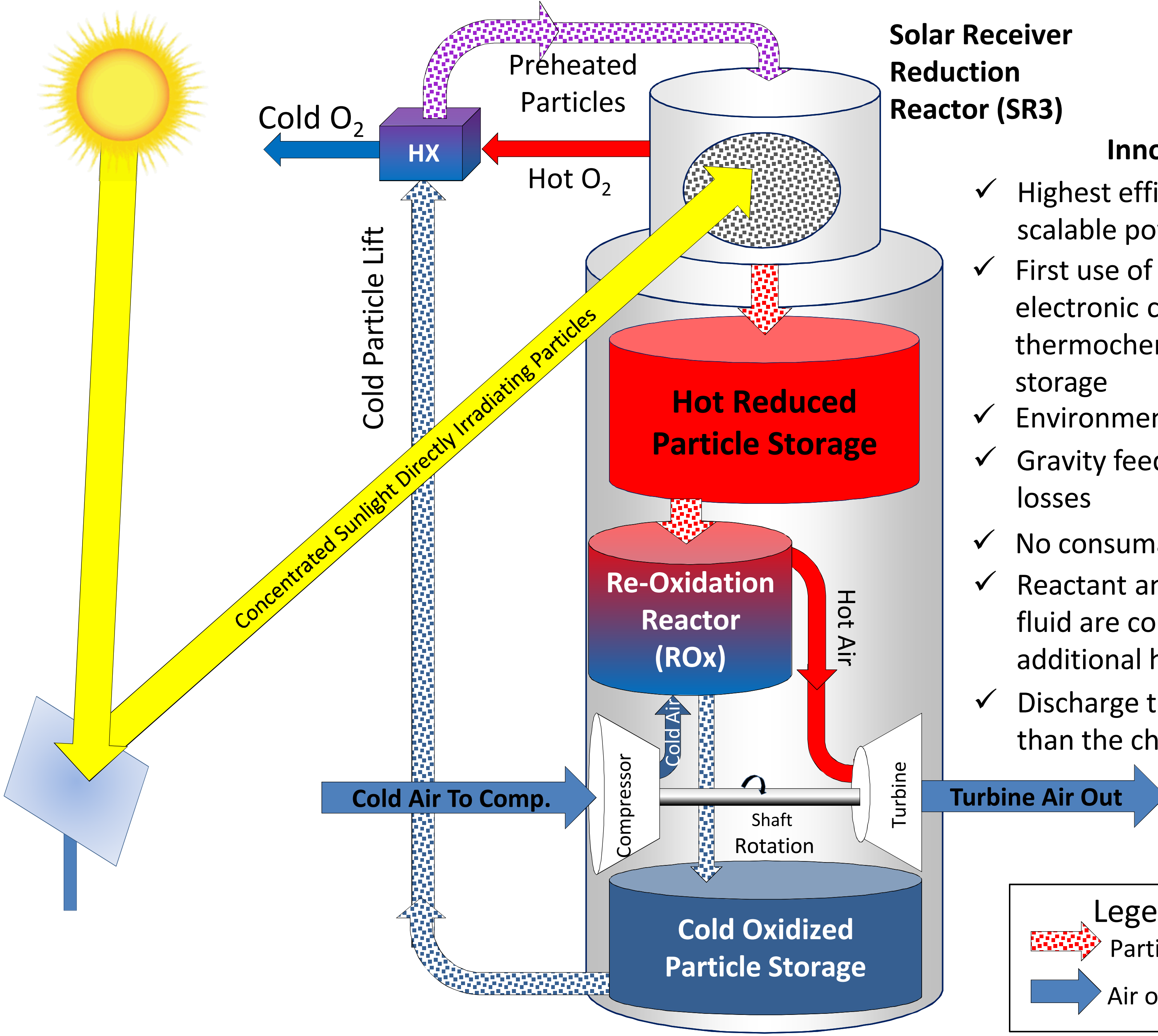
# Energy Storage



# Energy Storage

- Sensible (single-phase) storage
  - Low temperature melting-point molten salts
    - Reduce heating needs at night to prevent freezing
  - Stability of heat transfer fluids at higher temperatures
  - Solid storage (particles, graphite, concrete, ceramics)
- Phase-change materials
  - Use latent heat to store energy
- Thermochemical storage
  - Converting solar energy into chemical bonds (e.g., sulfur thermochemical cycle)

Molten-salt storage tanks at Andasol parabolic trough plant in Spain




**Innovation:**

- ✓ Highest efficiency, proven, scalable power cycle
- ✓ First use of mixed ionic-electronic conductors for thermochemical energy storage
- ✓ Environmentally benign
- ✓ Gravity feed – low parasitic losses
- ✓ No consumable catalysts
- ✓ Reactant and heat transfer fluid are combined – no additional heat exchanger
- ✓ Discharge temp. is greater than the charging temp.

# Outline

- What is Concentrating Solar Power (CSP)?
- Economics of CSP
- CSP Research Needs
- Summary

# Summary

- Concentrating Solar Power (CSP) provides utility-scale electricity
  - Uses mirrors to concentrate solar flux onto receiver
  - Hot working fluid converts heat to mechanical energy via heat engine (e.g., steam turbine, Stirling engine), which spins a generator for electricity
  - Extra heat can be used for thermal storage to generate electricity during night or cloudy periods

# Summary

- Market and Economics of CSP
  - Currently, only ~1% of U.S. energy consumption is from solar energy
    - ~90% from PV, ~10% from CSP
  - Current cost of CSP is significantly higher than fossil-fuel power plants
  - DOE SunShot goal is to reduce LCOE to $0.06/kWh by 2020
    - LCOE (levelized cost of energy) = annualized cost / annual energy production

# Summary

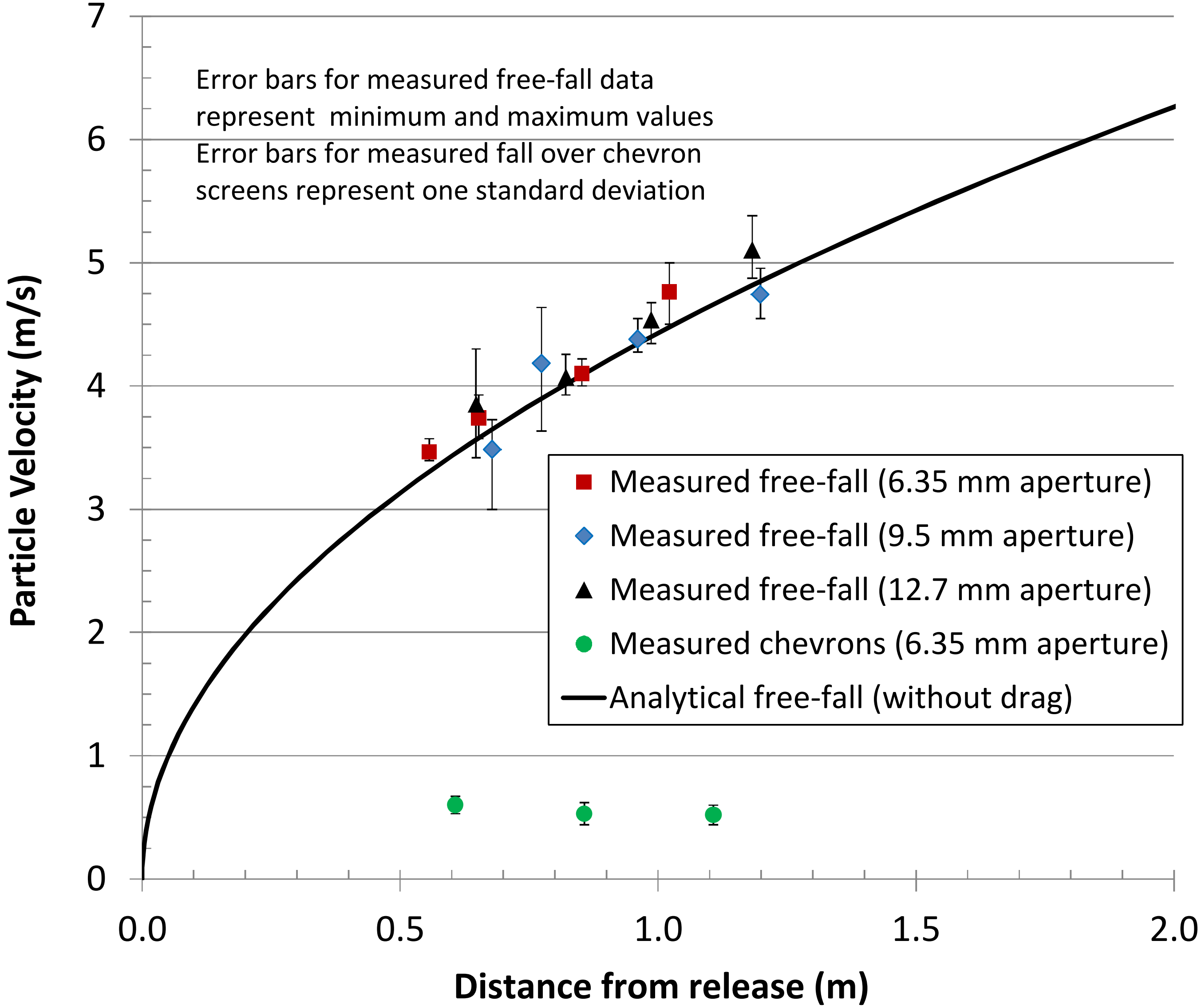
- Some Research Needs for CSP
  - Collectors (Mirrors) and Optical Performance
  - High-Temperature Receivers
  - Energy Storage
  - Efficient power cycles

# Questions?

Cliff Ho, (505) 844-2384, ckho@sandia.gov

# 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

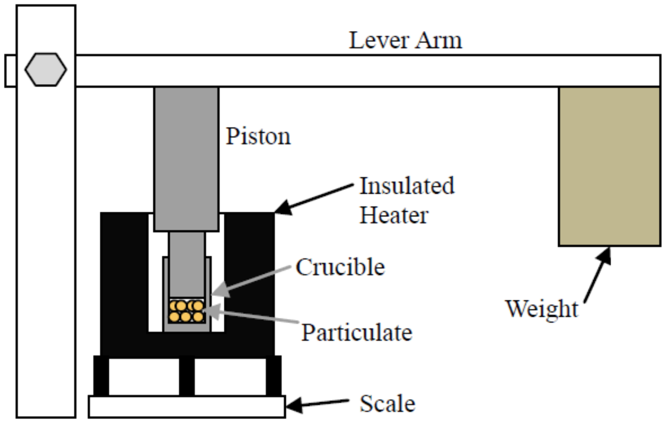



**Figure 2. Diagram of Experimental Setup**

**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**

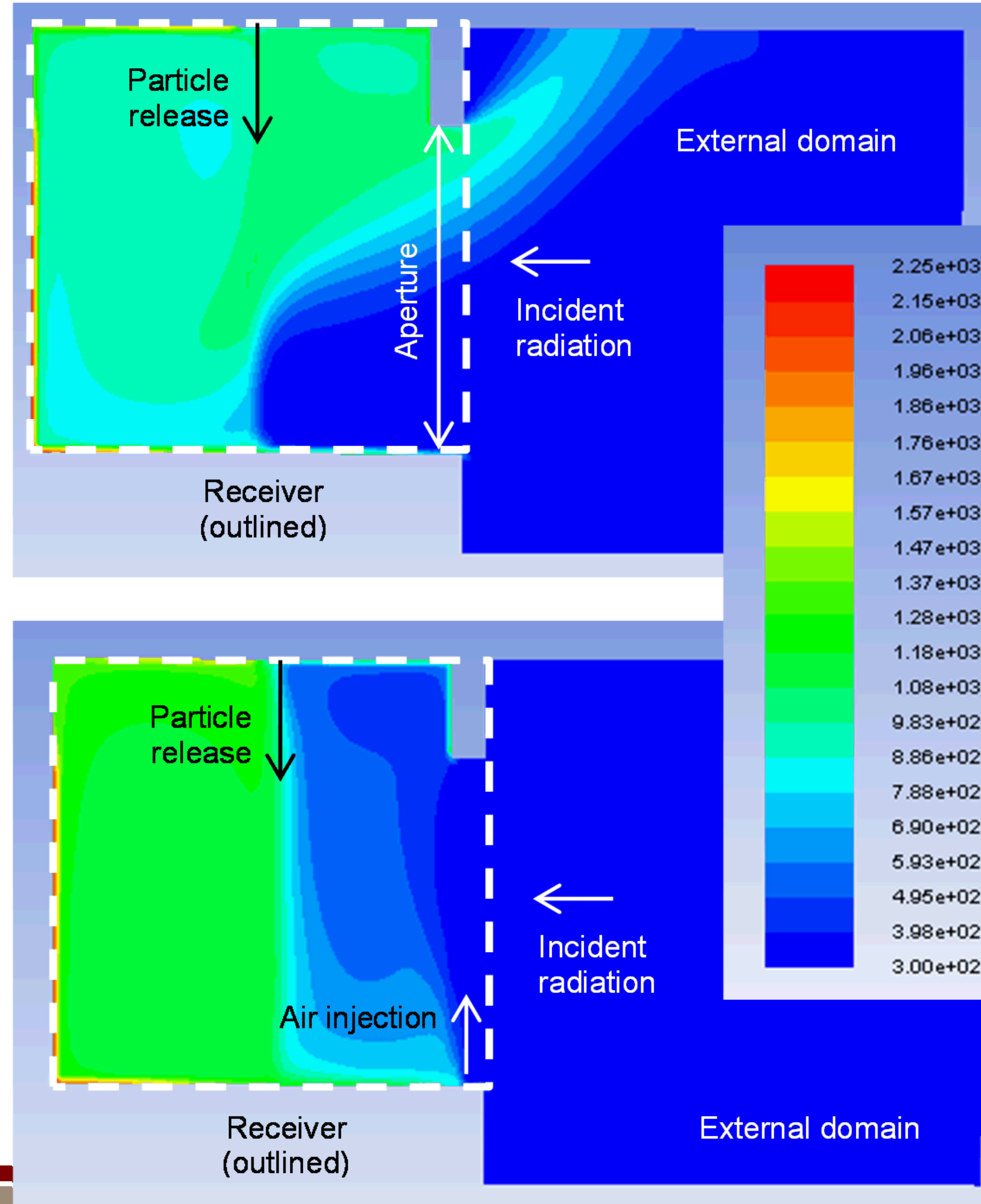
Al-Ansary et al., "Characterization and Sintering Potential of Solid Particles for Use in High Temperature Thermal Energy Storage System," SolarPACES 2013

# Design of Experiments

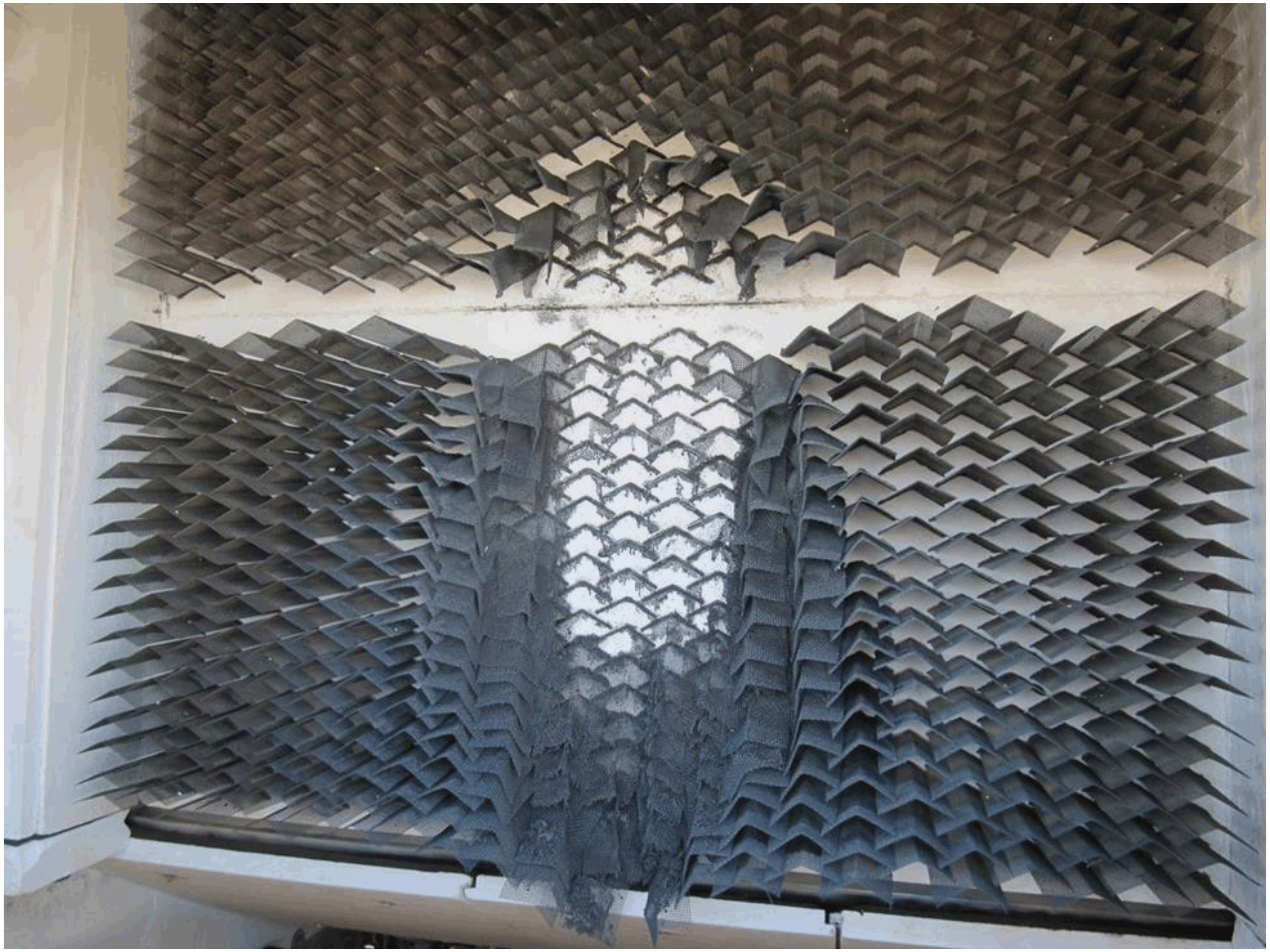
- Factors
  - Particle size
  - Particle mass flow rate
  - Particle release location
  - Air curtain blower speed
  - External wind
- Metrics
  - Particle loss
  - Particle curtain spread

# 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



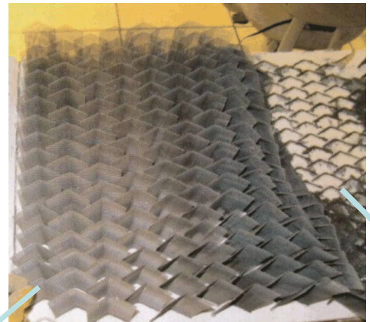
# Failure of Mesh Structures

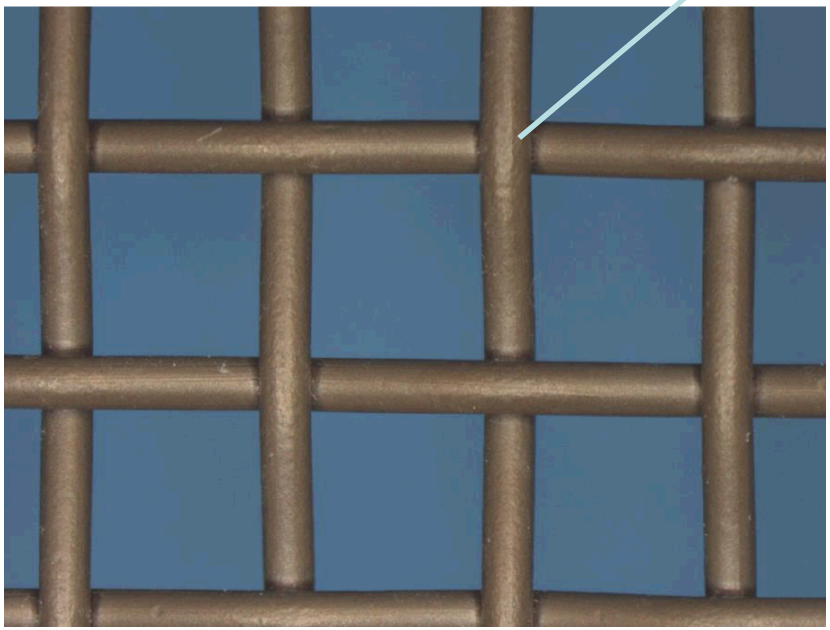


Failure of 316 SS mesh structures on July 24, 2015
~700 suns at ~1000 C (steel)

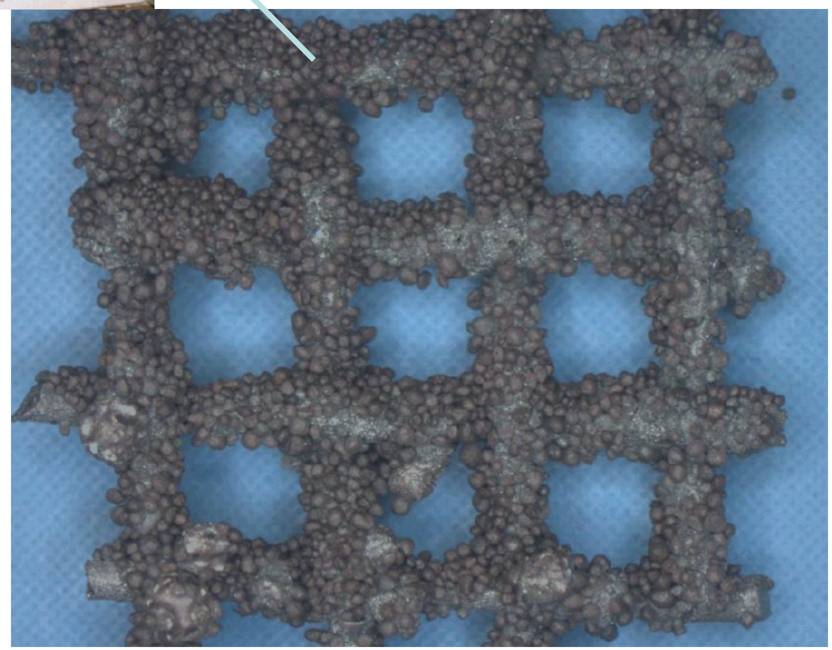
# Receiver Mesh Structures


# SS316 Mesh Failure Analysis



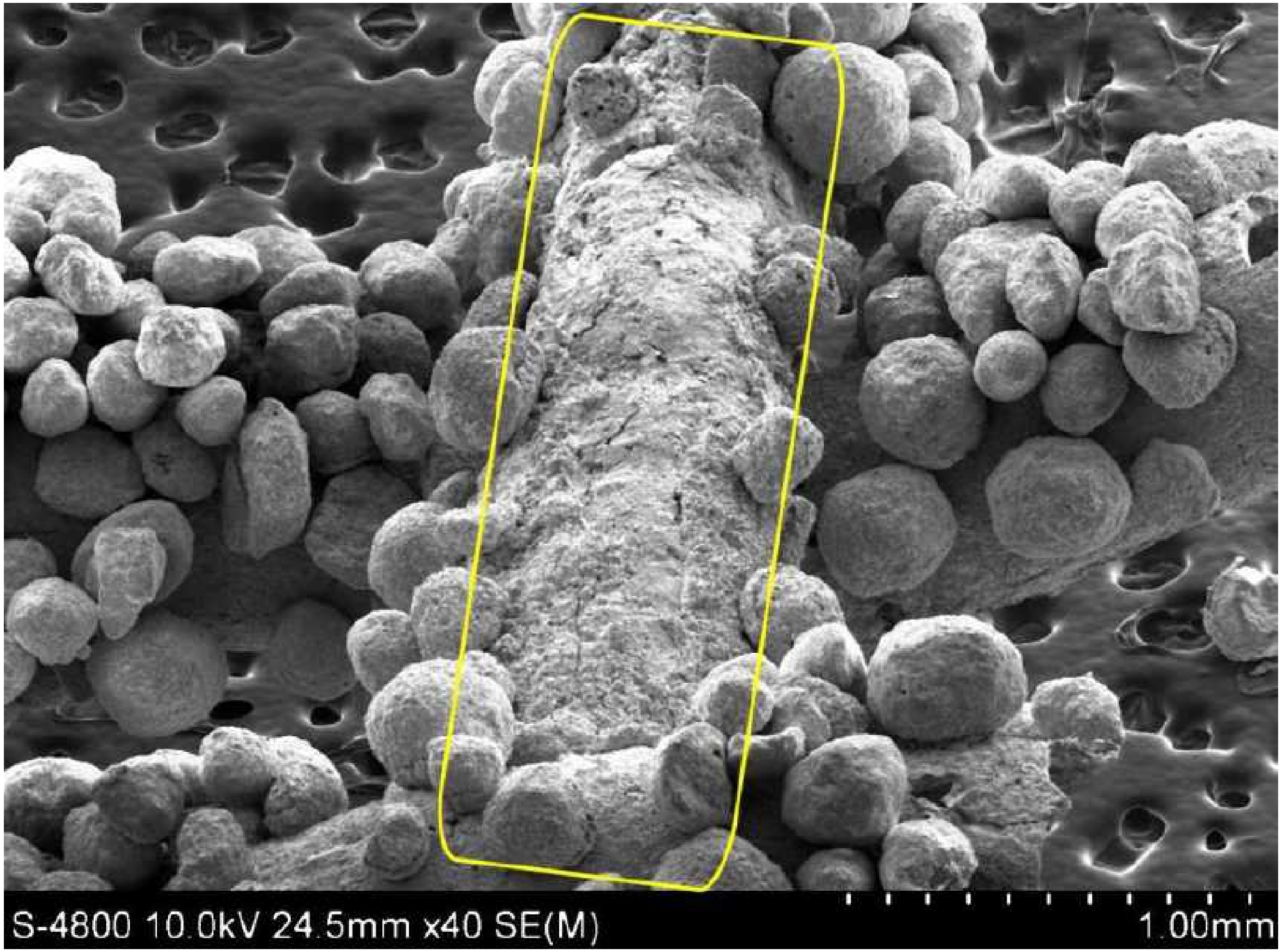


Mesh located far from failed region



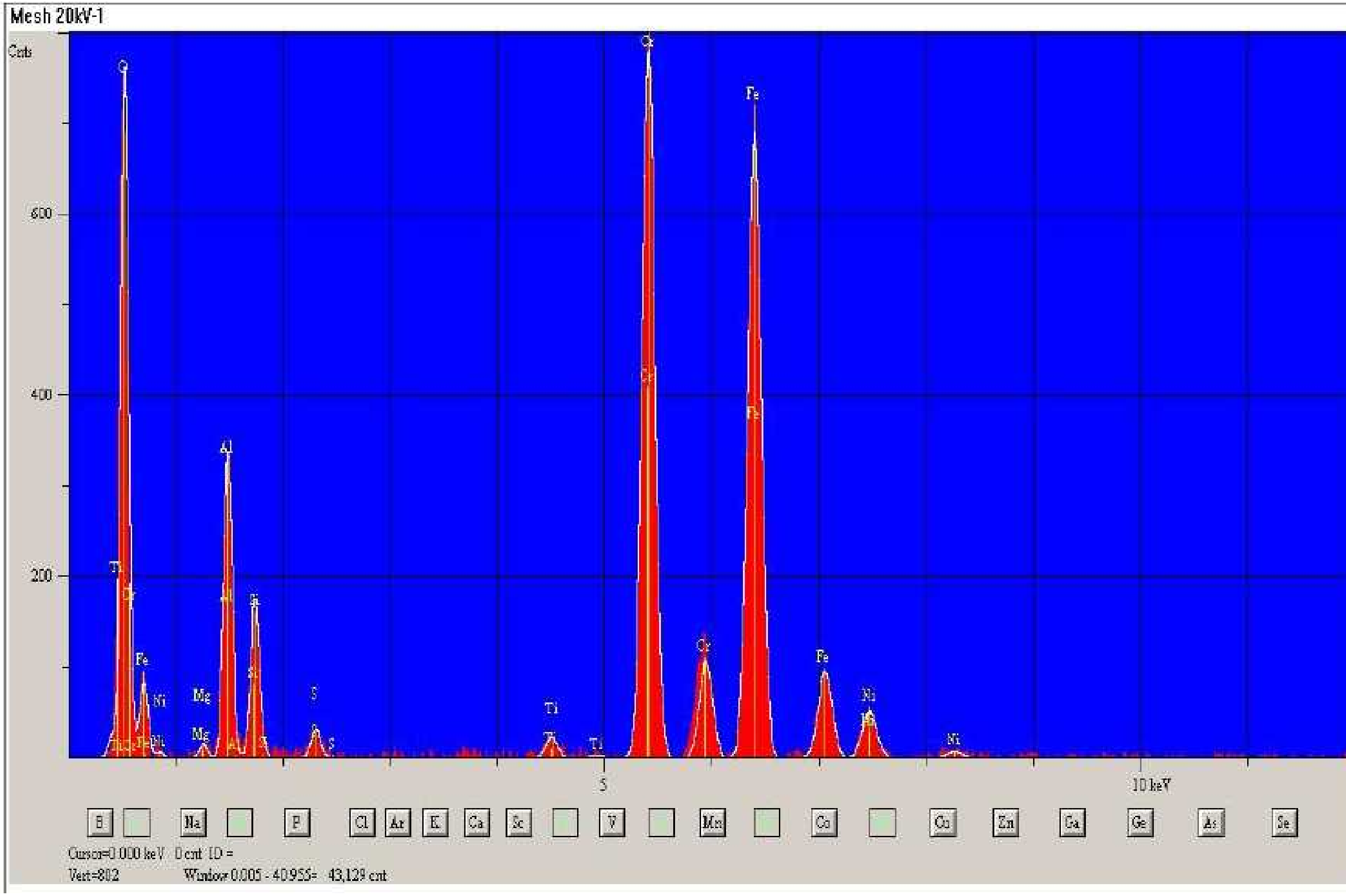
Mesh located within failed region
(ceramic particles sintered on mesh)

# SS316 Mesh Failure Analysis




SEM of oxidized mesh

# SS316 Mesh Failure Analysis

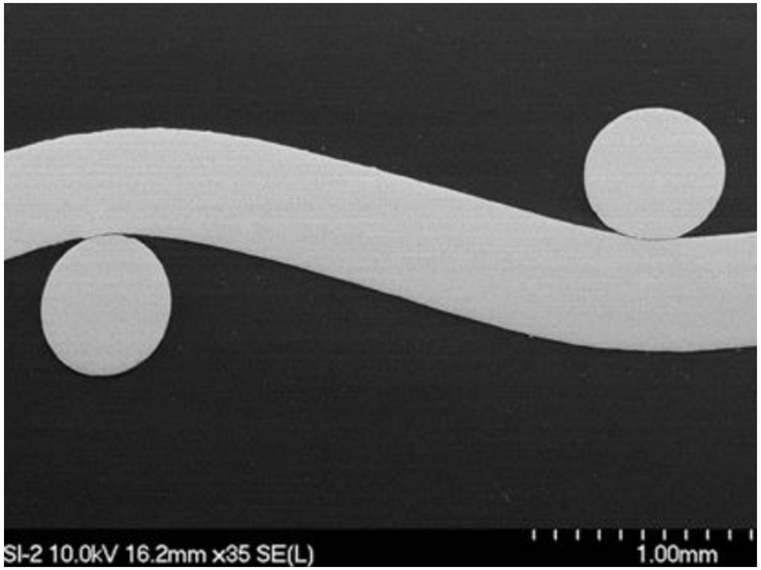


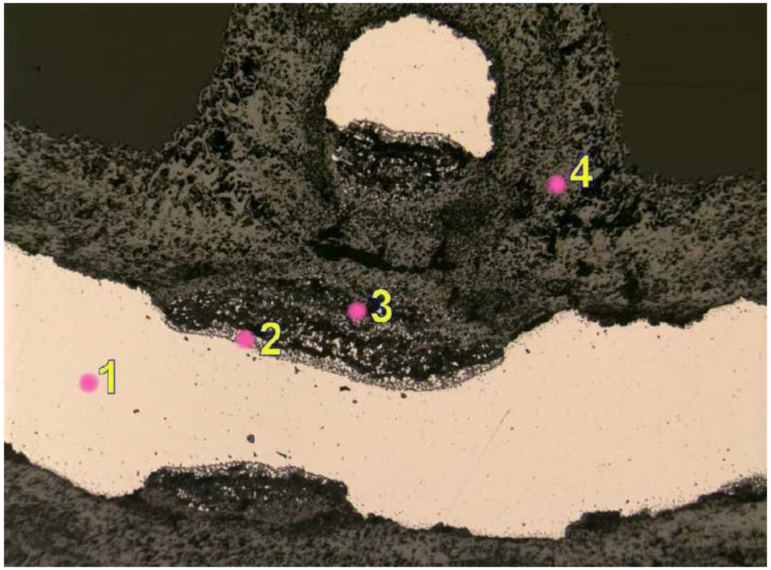

| El. | Line | Intensity (c/s) | Error 2-sig | Conc | Units |
|---|---|---|---|---|---|
| O | Ka | 309.55 | 8.364 | 31.867 | wt.% |
| Mg | Ka | 7.47 | 1.733 | 0.400 | wt.% |
| Al | Ka | 167.03 | 6.407 | 6.944 | wt.% |
| Si | Ka | 90.53 | 5.118 | 3.247 | wt.% |
| S | Ka | 17.73 | 3.849 | 0.560 | wt.% |
| Ti | Ka | 15.57 | 3.479 | 0.495 | wt.% |
| Cr | Ka | 570.73 | 11.135 | 22.536 | wt.% |
| Fe | Ka | 539.81 | 10.764 | 30.612 | wt.% |
| Ni | Ka | 42.84 | 3.725 | 3.339 | wt.% |
| | | | | 100.000 | wt.% |

kV 20.0
Takeoff Angle 35.0°
Elapsed Livetime 20.0

FESEM/EDS of oxidized mesh

# SS316 Mesh Failure Analysis



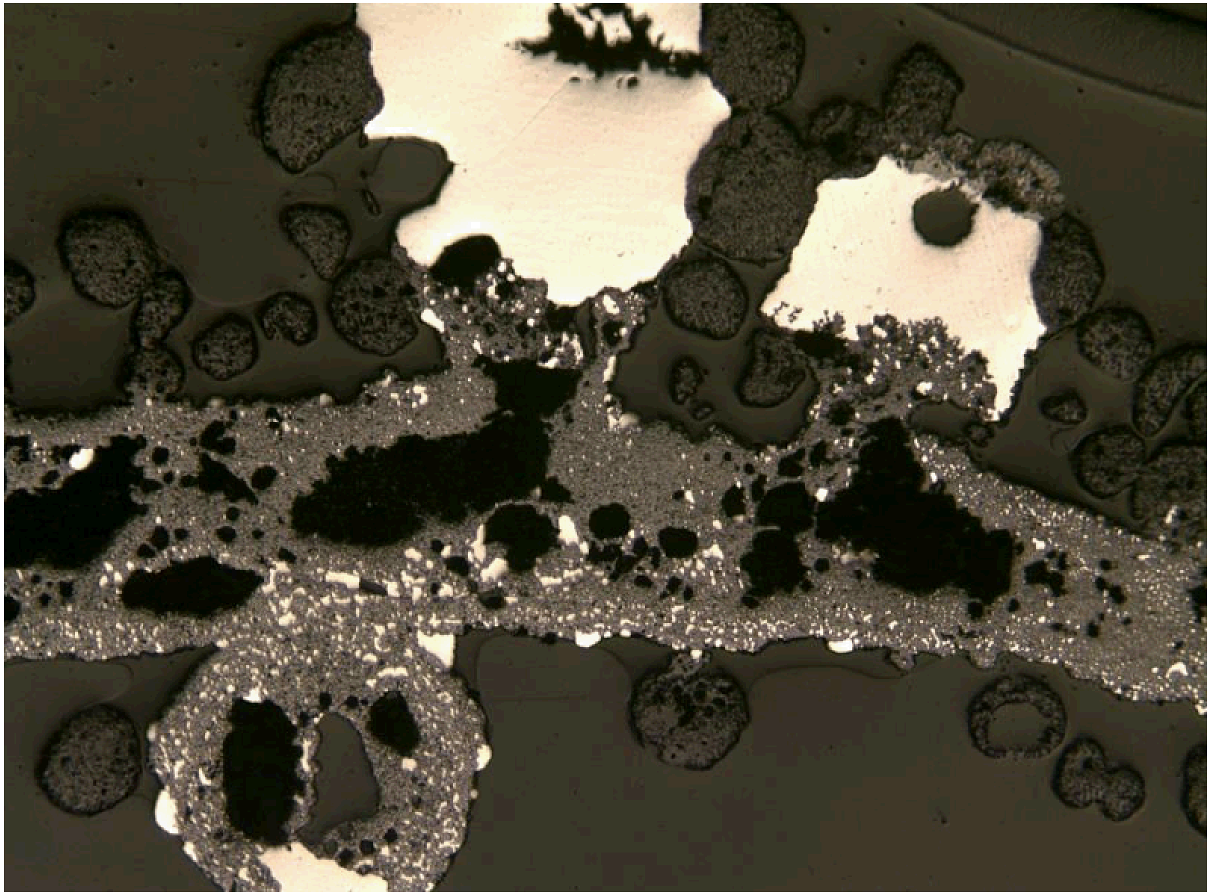



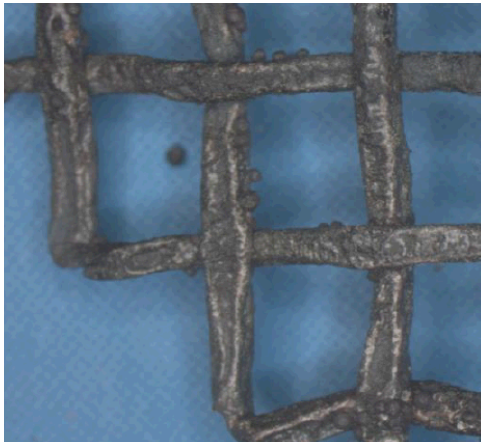

| | Fe | Cr | Ni | Mo | O | Al | Si |
|---|---|---|---|---|---|---|---|
| | (Wt% EDS semi-quant, standardless EDS) | | | | | | |
| **Location 1** <br> **Wire core** | 67 | 20 | 6.7 | 5.2 | - | - | - |
| **Location 2** <br> **"intermetallic layer"** | 19 | 4.45 | 44 | 11 | 19 | 1.64 | 1.34 |
| **Location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

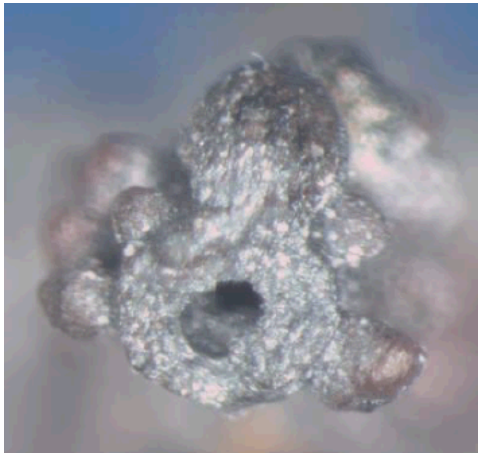
Top left: cross-sectional view of intact wire mesh

Top right: cross-sectional view of oxidized wire mesh

# 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)

# Acknowledgments

SunShot U.S. Department of Energy Award # DE-EE0000595-1558

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  - Birgit Gobereit, Lars Amsbeck, Reiner Buck

Need to reduce the levelized cost of electricity (LCOE) from solar

# What is LCOE?

- Levelized Cost of Electricity (Energy) in $/kWh

$$LCOE = \frac{\text{Annualized Cost of Power Plant (\$)}}{\text{Annual Net Energy Production (kWh)}}$$

**where:**

Power [Watt] = [Joules / second]

Energy [Joule] = [Watt] * [second] = [kW] * [hour] * (1000 W/kW) * (3600 sec/hour)