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Concentrating Solar Power - Receivers

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Concentrating Solar Technologies
Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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What are Receivers?

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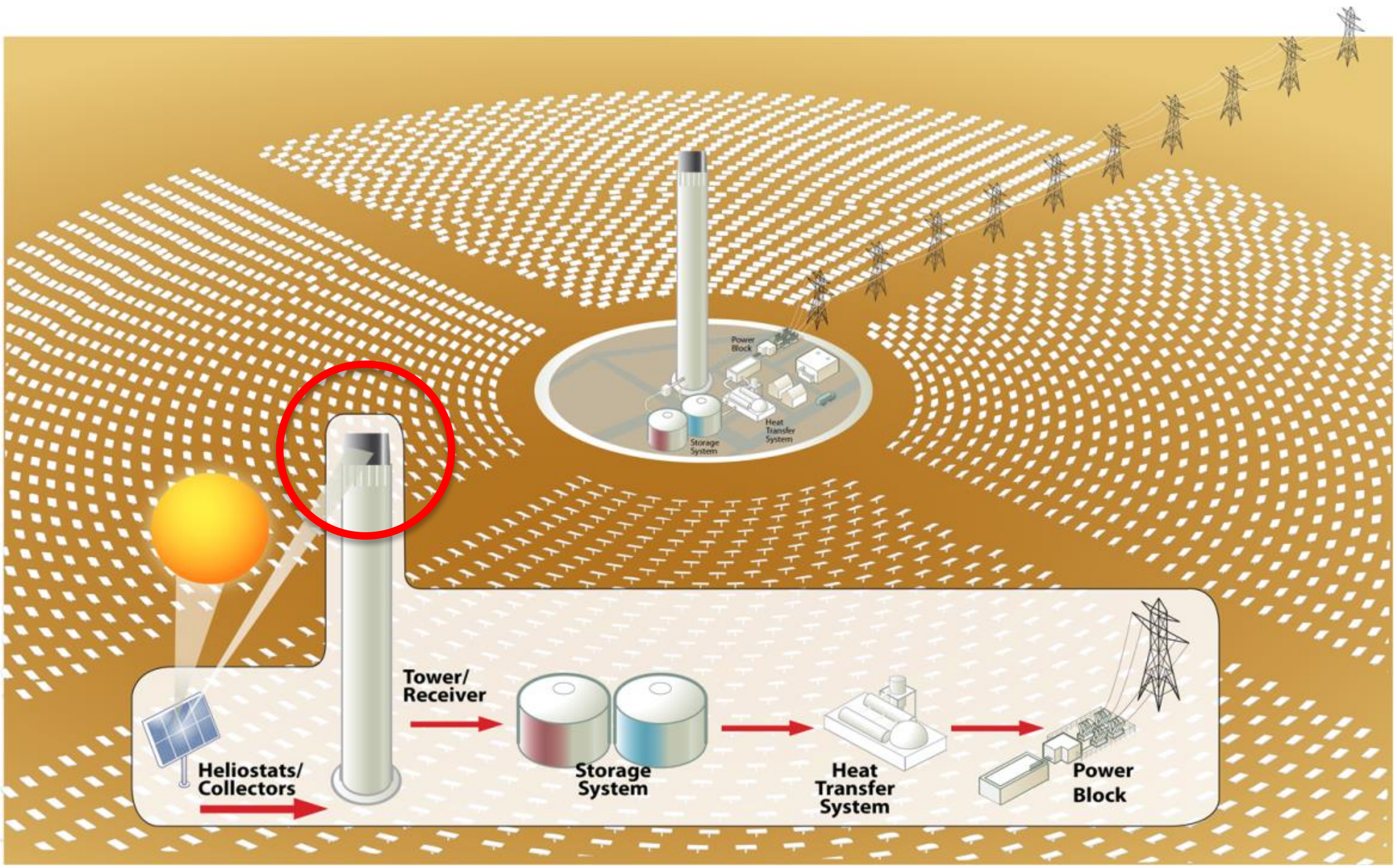


Objectives

- Higher-efficiency, higher-temperature power cycles are being pursued
  - US DOE SunShot goal of \$0.06/kWh (with storage)
- Need high efficiency, high-temperature receivers
  - $T_{HTF,out} \geq 700^\circ C$
  - $\eta_{annual} \geq 90\%$
  - Lifetime ≥ 10,000 thermal cycles
  - Cost ≤ \$150/kW_{th}

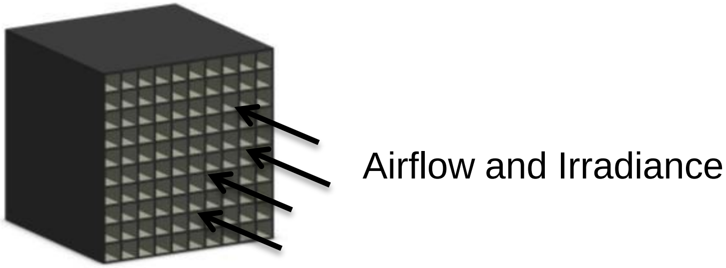
Types of Receivers & Challenges

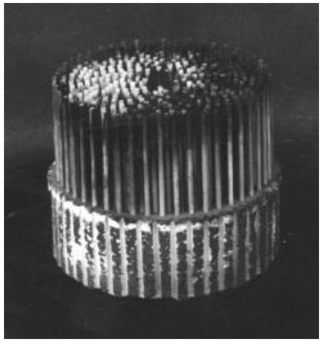
- Gas-Based Central Receivers
  - Flow instabilities, low efficiency, material durability, heat exchange, storage
- Liquid-Based Central Receivers
  - Instability of molten salts > 600 C, material durability, selective absorbers
- Solid-Particle Central Receivers
  - Particle/fluid heat exchange, high radiative/convective loss, particle attrition

Gas-Based Central Receivers

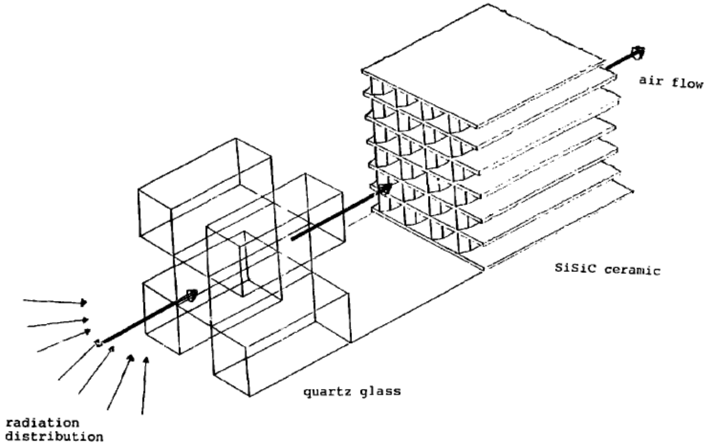
Gas-Based Central Receivers

- Volumetric Air Receivers
  - Benefits
    - T > 700 °C
    - Demonstrated technology
  - Challenges
    - Flow instabilities
    - Material durability
    - Low efficiency (50 – 60%)
    - Heat storage and heat exchange





“Porcupine”
(Karni et al., 1998)

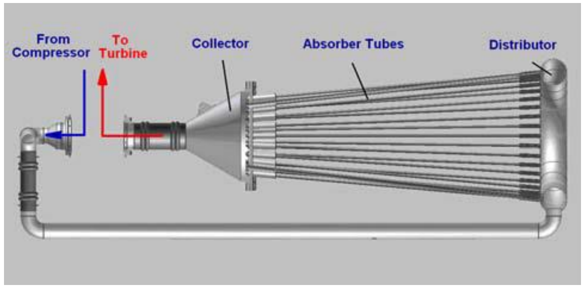


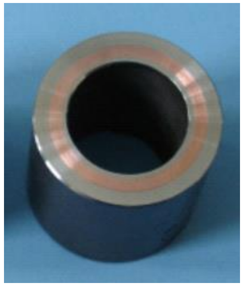
Selective volumetric receivers

- (Left image) Pitz-Paal et al. (1991)
- Menigault et al. (1991)

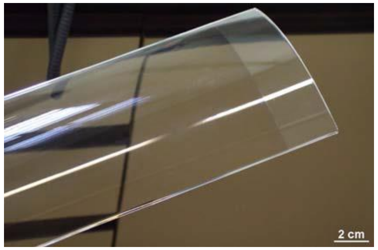
Gas-Based Central Receivers

- Tubular gas receivers
  - Benefits
    - T > 700 °C
    - Can heat working fluid directly (e.g., Brayton cycles)
  - Challenges
    - Heat transfer to gas
    - Material durability
    - Low efficiency (50 – 60%)
    - Heat storage





Copper in between Inconel to increase heat transfer



Segmented glass to form window to reduce heat losses

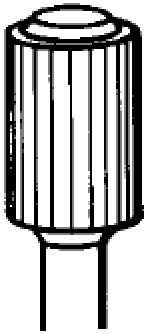
Amsbeck et al. (2009, 2010), Heller et al. (2009)

Liquid-Based Central Receivers

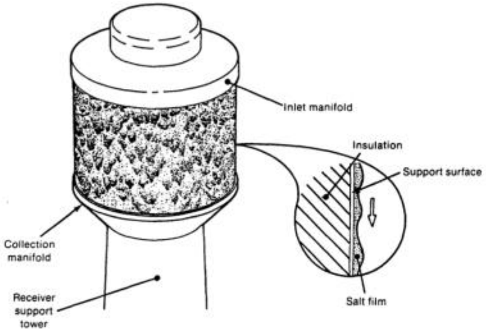
Liquid-Based Central Receivers

- Tubular liquid receivers
  - Benefits
    - Good efficiency (up to 90%)
    - Storage (molten salt)
  - Challenges
    - Limited temperature with existing nitrate salts (T < 600 °C)
    - Material durability, selective absorbers

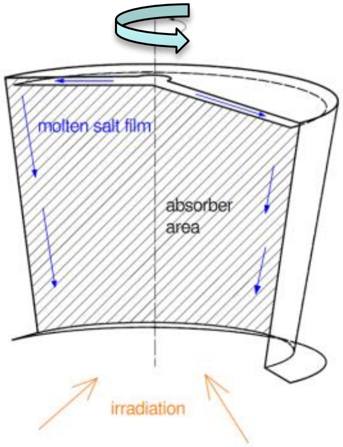
Solar Two Molten Salt Receiver (Pacheco, 2002)



Liquid sodium (Falcone, 1986) or fluoride salt receiver (Forsberg et al., 2007)



External direct absorption falling film (Bohn & Green, 1989)



Internal direct absorption falling film (Wu et al., 2011)

Bladed Tubular Receiver Designs

- Australian National University
  - Dr. John Pye
    - Co-inventor on two patents dealing with bladed and fractal-like designs
  - $3.3M project awarded by Australian Renewable Energy Association (ARENA) on "CSP Receivers: Bladed Designs and Active Airflow Control"
    - Complementary work includes water- and wind-tunnel testing, integration of air-curtains, techno-economic analyses, commercialization

Australian National University

THE UNIVERSITY OF ADELAIDE AUSTRALIA

CSIRO

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Problem Statement

- Radiative heat loss is maximized in conventional receiver designs due to reflection and thermal radiation to environment
- Improvements in receiver efficiency found to have significant impact on reducing levelized cost of energy for CSP*
- Previous research has focused on selective coatings
  - Lack durability in air at high temperatures
  - Difficult to achieve high solar absorptance and low thermal emittance

110 MW Crescent Dunes Plant
Tonopah, NV

390 MW Ivanpah Solar Electric Generating System

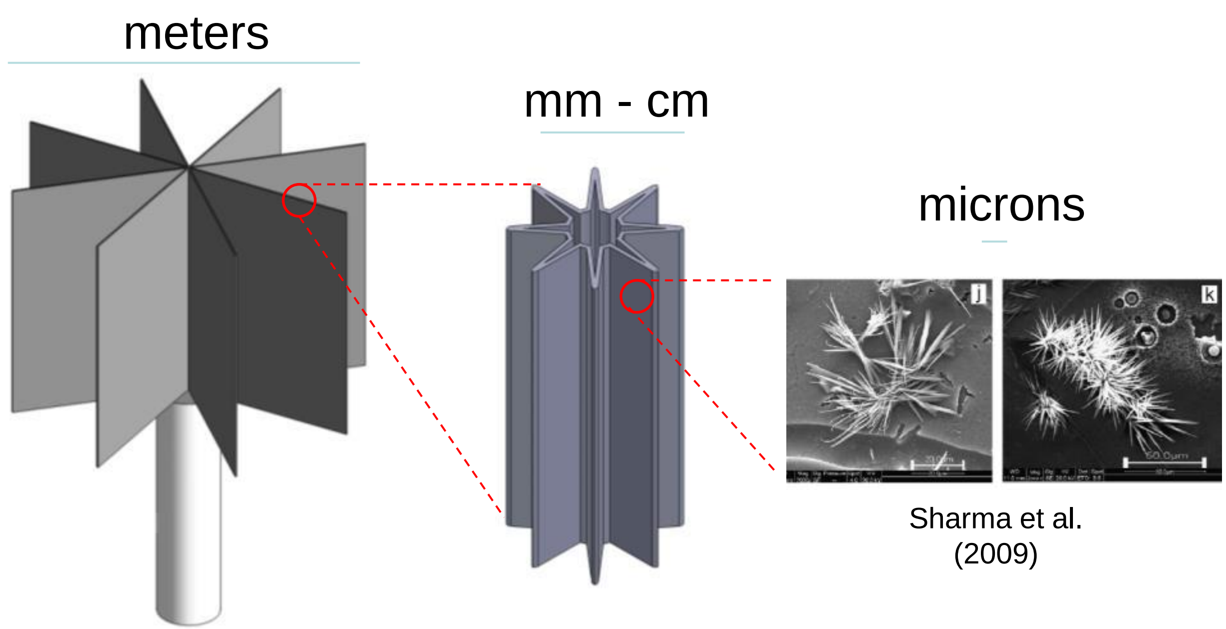
*Power Tower Technology Roadmap and Cost Reduction Plan (SAND2011-2419)

Objectives – Bladed Receivers

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

~10 m

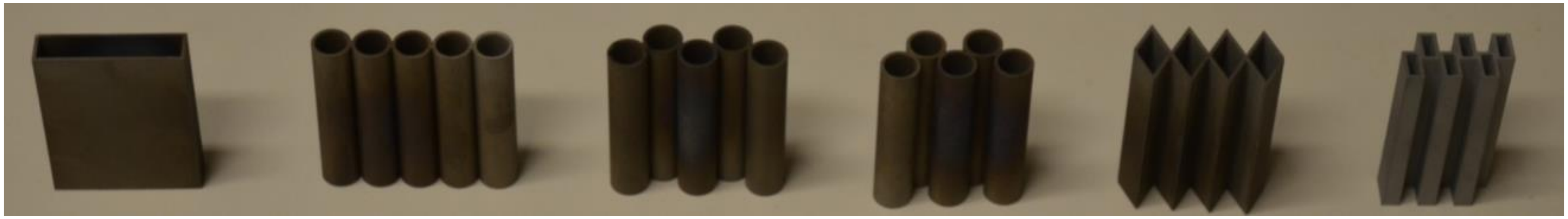
Conventional cylindrical solar receiver



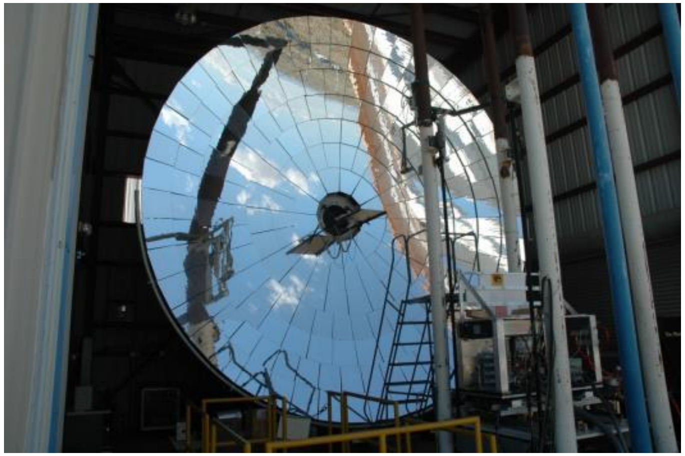
New fractal-like designs with light-trapping and low-emittance properties at multiple scales

Meso-Scale Testing

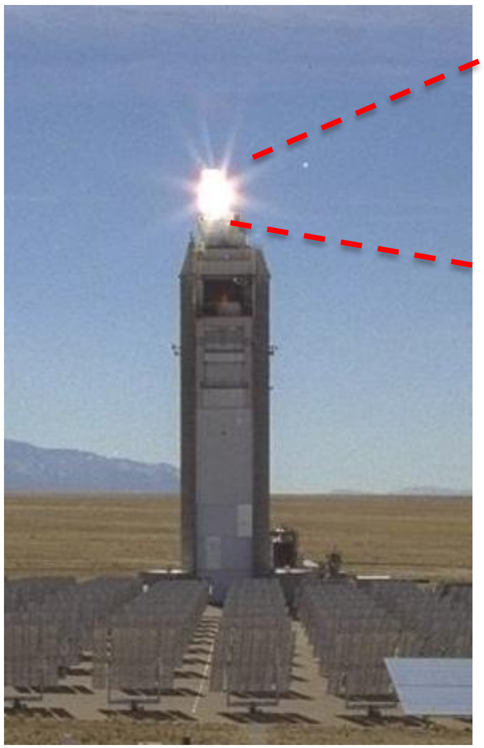
- Irradiance distribution measured for different meso-scale geometries made from Inconel 718
- Ray-tracing performed to evaluate effective solar absorptance

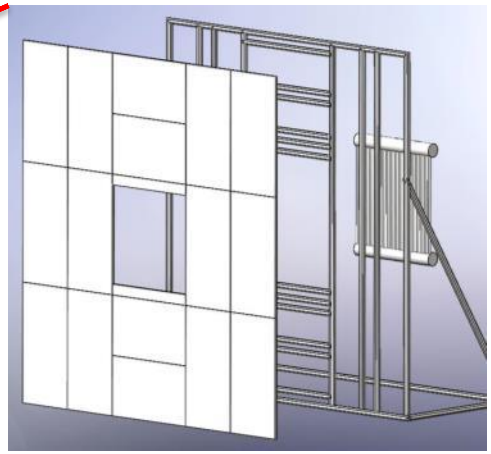


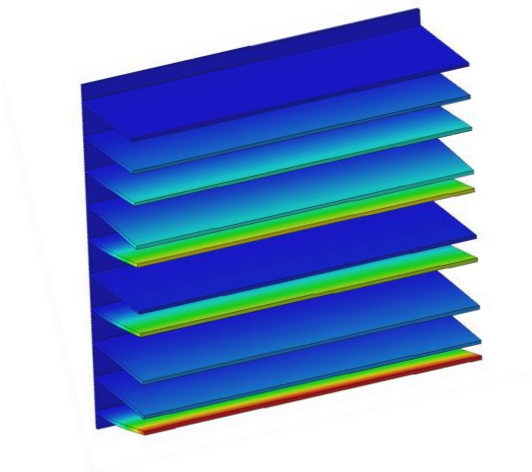
Flat Plate | **Tubes 0° Offset** | **Tubes 30° Offset** | **Tubes 45° Offset** | **Diamonds** | **Rectangular Tubes**

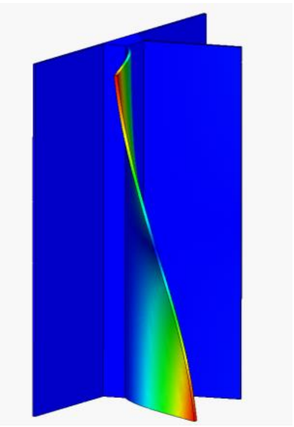


Macro-Scale Design and Testing





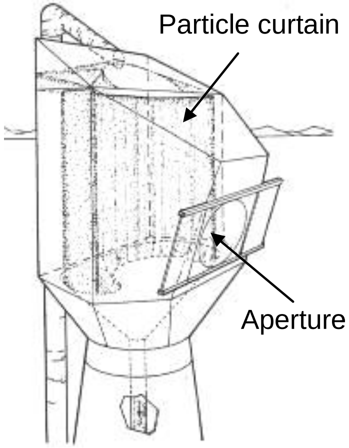




Solid Particle Central Receivers

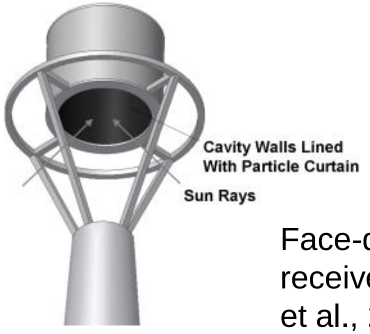
Solid Particle Central Receivers

- Falling Particle Receivers
  - Benefits
    - High temperatures (T > 700 °C)
    - Storage
    - Increased fluxes
  - Challenges
    - Need to increase thermal efficiency (prototype 50%)
    - Particle attrition
    - Particle/fluid heat exchange

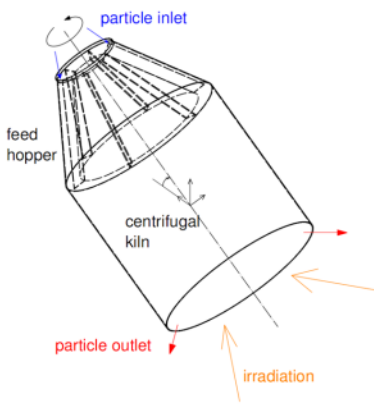


Falling particle receiver (Falcone et al., 1985)

On-sun prototype test and analysis (Siegel and Kolb, 2008; Ho et al., 2009)

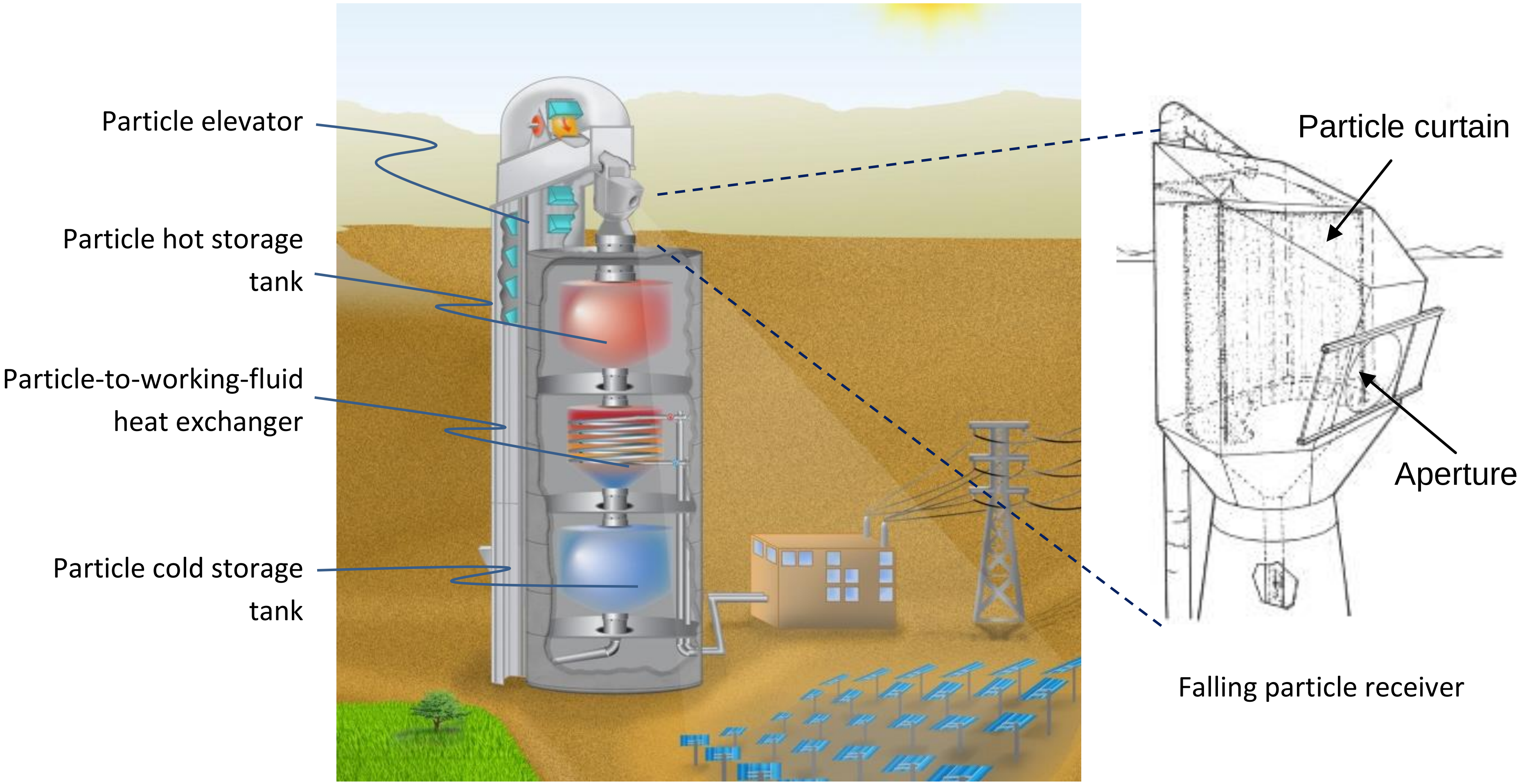


Face-down falling particle receiver with recirculation (Roger et al., 2011; Khalsa et al., 2011)



Falling particle rotating kiln (Wu et al., 2011)

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

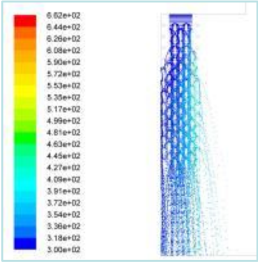


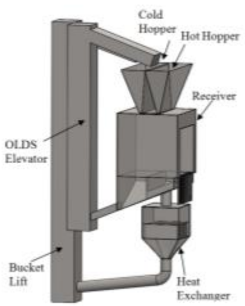
General Approach

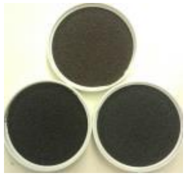
Phase 1
- Modeling, design, proof-of-concept testing

Phase 2
- Component testing, model validation, design optimization

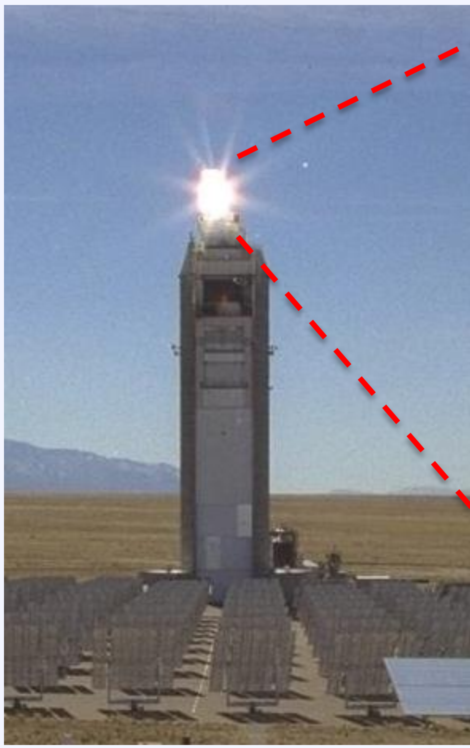
Phase 3
- Prototype development for on-sun testing

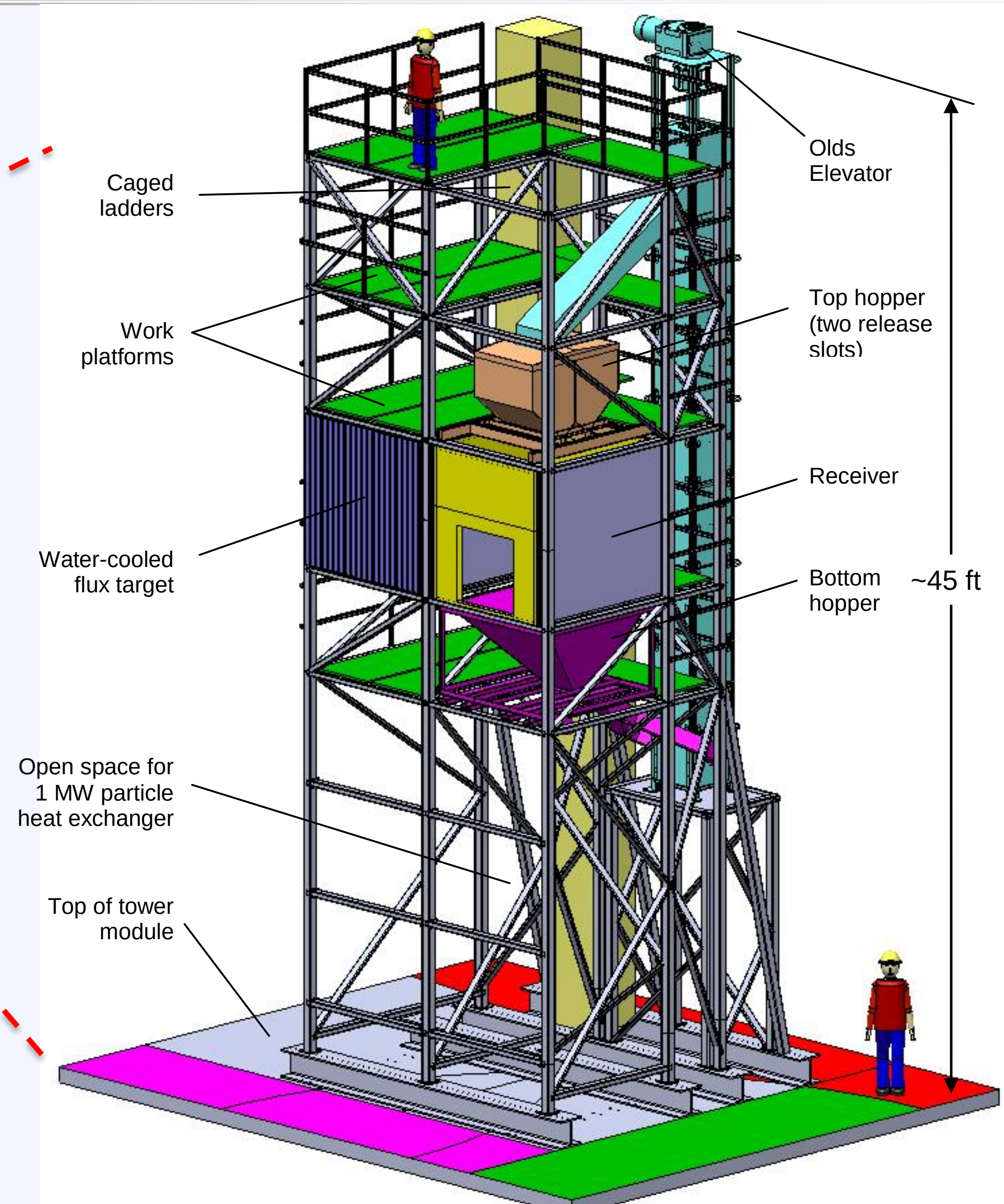






Prototype System Design

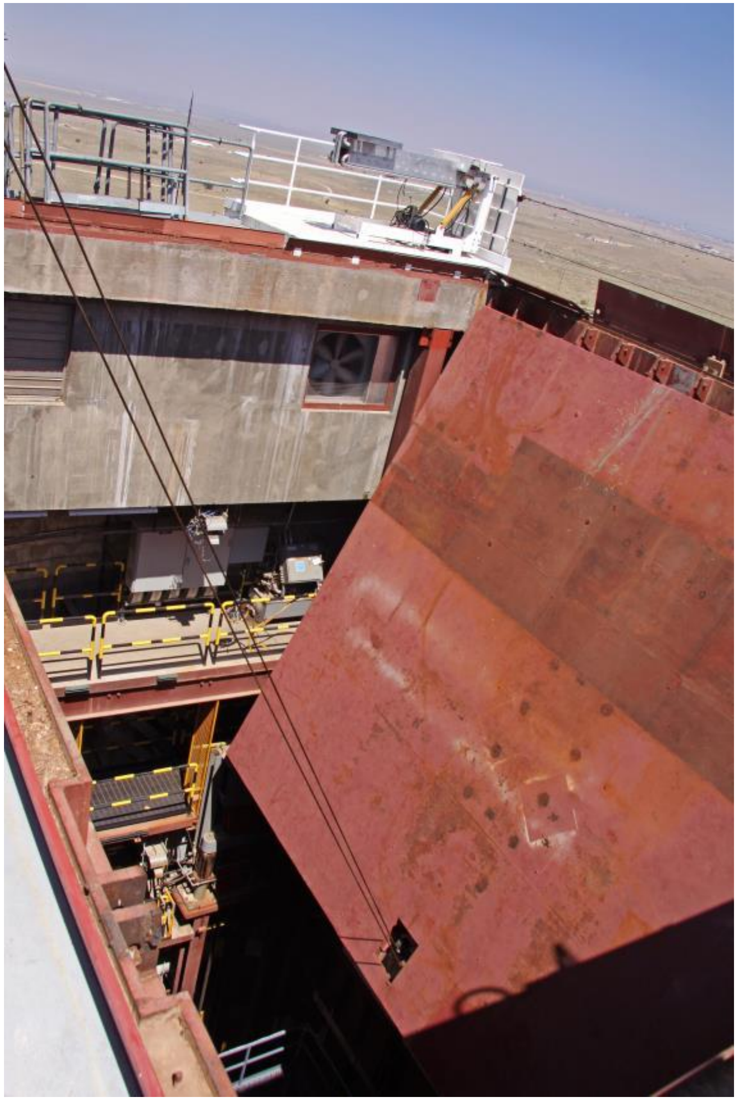




SunShot
U.S. Department of Energy

Lifting the system to the top of the tower

Lifting the system to the top of the tower



Lifting the system to the top of the tower

On-Sun Tower Testing

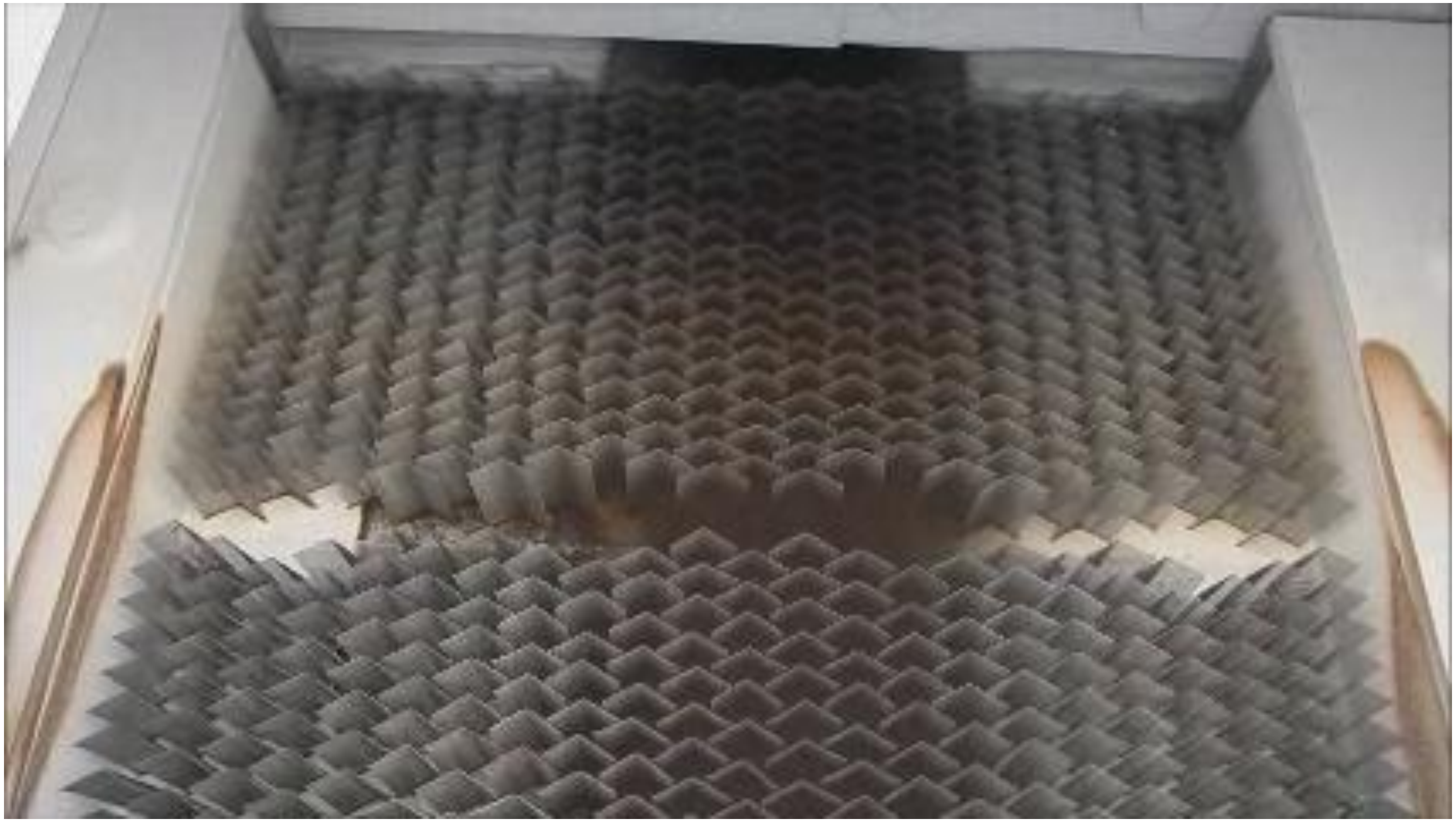
On-Sun Tower Testing

Over 300 suns on receiver
(June 25, 2015)

On-Sun Tower Testing

Over 300 suns on receiver
(June 25, 2015)

On-Sun Tower Testing



Particle Flow Through Mesh Structures
(June 25, 2015)

Summary

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  - Flow instabilities, low efficiency, material durability, heat exchange, storage
- Liquid-Based Central Receivers
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Research Opportunities?

- New receiver designs
  - Bladed and fractal-like receiver designs
    - Increased solar irradiance on receiver tubes
    - Reduced radiative and convective heat loss
  - High-temperature, high-pressure receiver tubing (700 C, 20 MPa) for direct sCO_2 heating; durable selective absorbers
- Advanced heat transfer fluids and particles
  - Liquid metals (e.g., sodium)
  - Sodium vapor
  - High-temperature molten salts with low melting points
  - Highly absorptive solid particles with low attrition
- High-temperature heat exchangers
  - Micro-channels (Heatric), pulsating heat pipes, particle/fluid heat exchangers (shell-and-tube, fluidized bed)