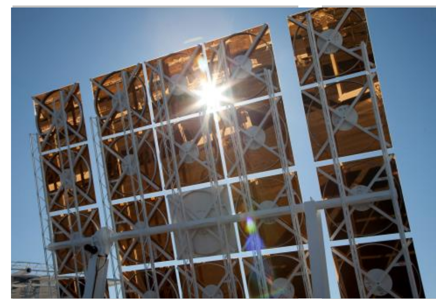
SAND2017-13126PE

Particle Research at Sandia National Laboratories for Concentrating Solar Power

Exceptional service in the national interest



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SAND2017-XXXX

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Where is Albuquerque, New Mexico?

Sandia National Laboratories

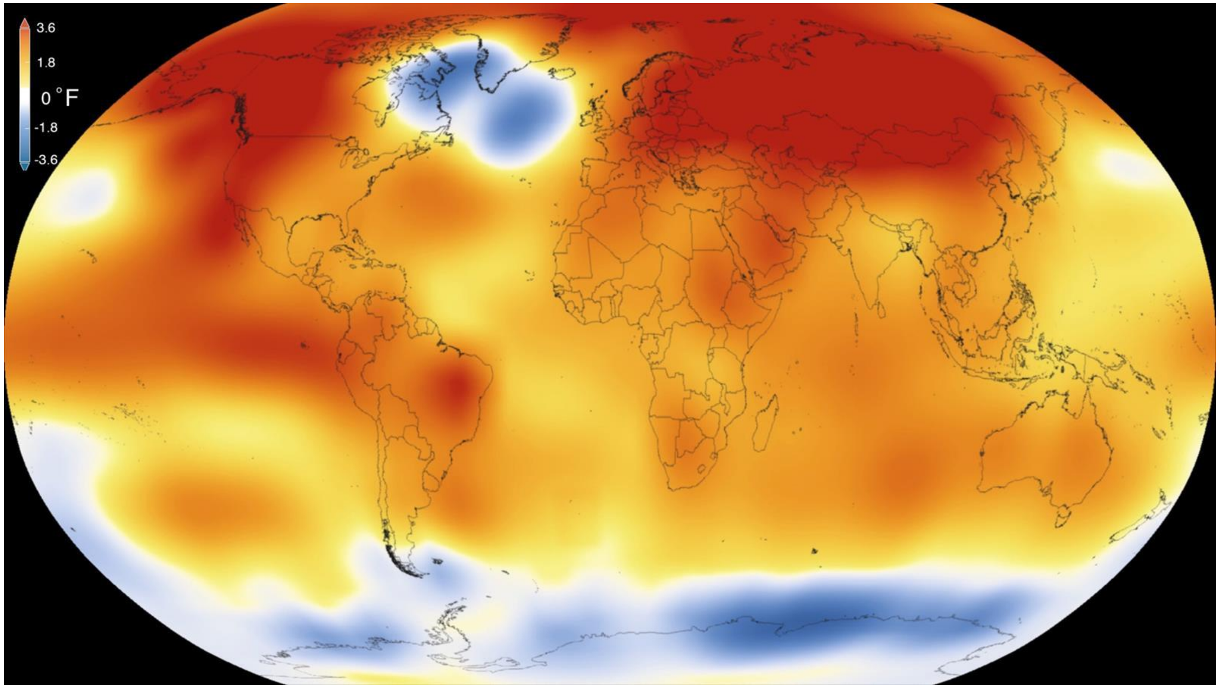
Overview

Sandia National Laboratories

- Background
- Particle Research at Sandia
  - Particle Receivers for Renewable Energy
  - Thermochemical Particle Storage
  - Solar Fuel Production Using Reactive Particles
- Summary

Motivation

- Renewable energy technologies critical to energy future
  - Reduce carbon emissions and pollution

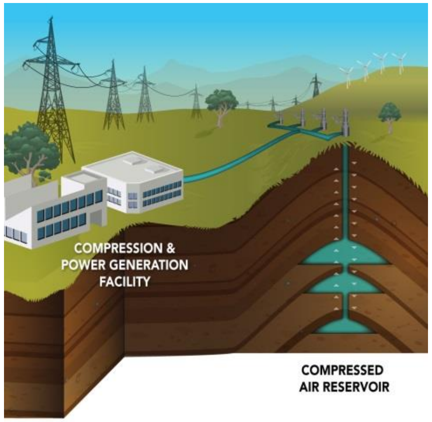


2016 – Warmest Global Year on Record (since 1880) – Colors indicate temperature anomalies (NASA/NOAA; 20 January 2016).

Most warming occurred in past 35 years; 15 of 16 warmest years on record since 2001

Problem Statement

- Current renewable energy sources are intermittent
  - Causes curtailment or negative pricing during mid-day
  - Cannot meet peak demand in evenings
- Available energy storage options for solar PV & wind
  - Large-scale battery storage is expensive
    - $\$0.20/kWh_e$ - $\$1.00/kWh_e$
  - Compressed air and pumped hydro – geography and/or resource limited



Need

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

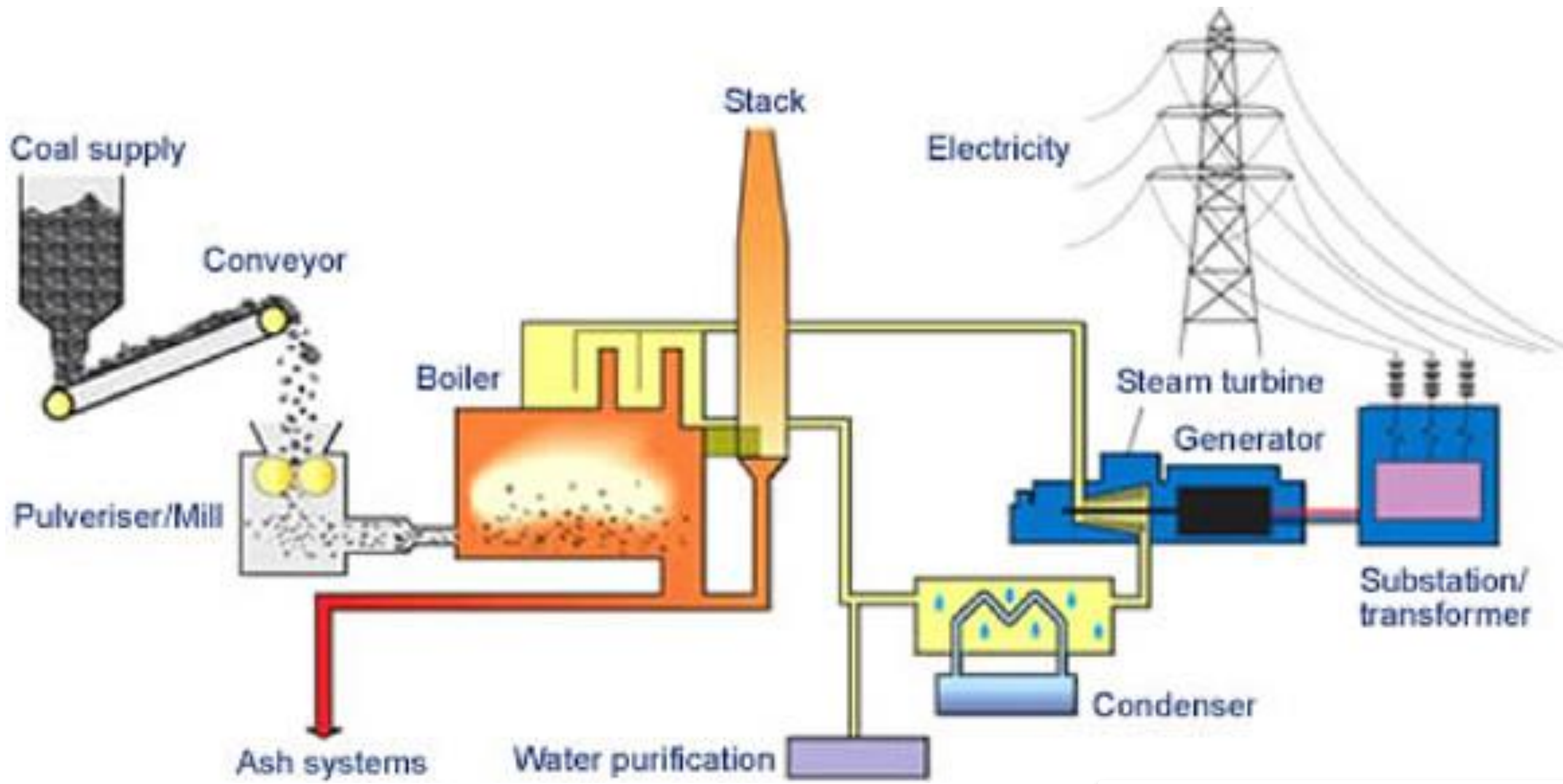
➡ Concentrating solar power (CSP) with thermal energy storage

- 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)
  - Thermochemistry & Solar Fuels (>1000 ˚C)

➡ High-temperature particle receivers for concentrating solar power

What is Concentrating Solar Power (CSP)?

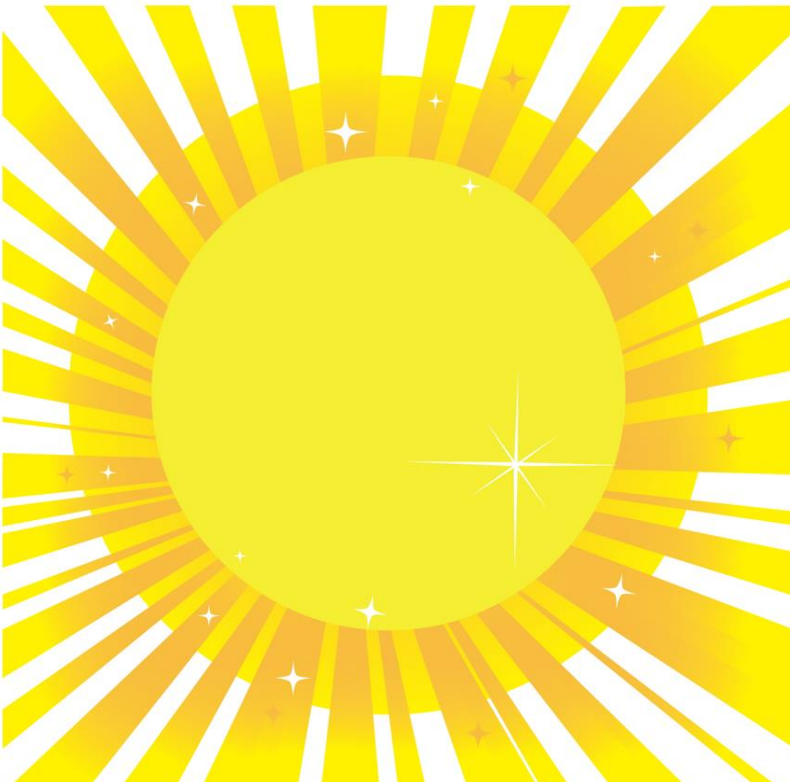
Conventional power plants burn fossil fuels (e.g., coal, natural gas) or use radioactive decay (nuclear power) to generate heat for the power cycle

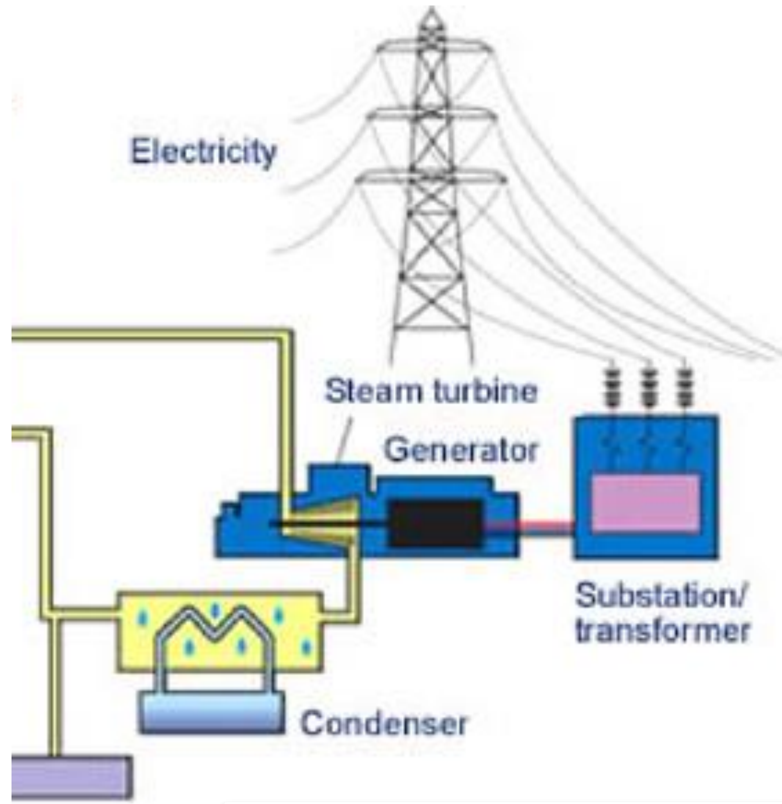


Coal-Fired Power Plant

What is Concentrating Solar Power (CSP)?

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

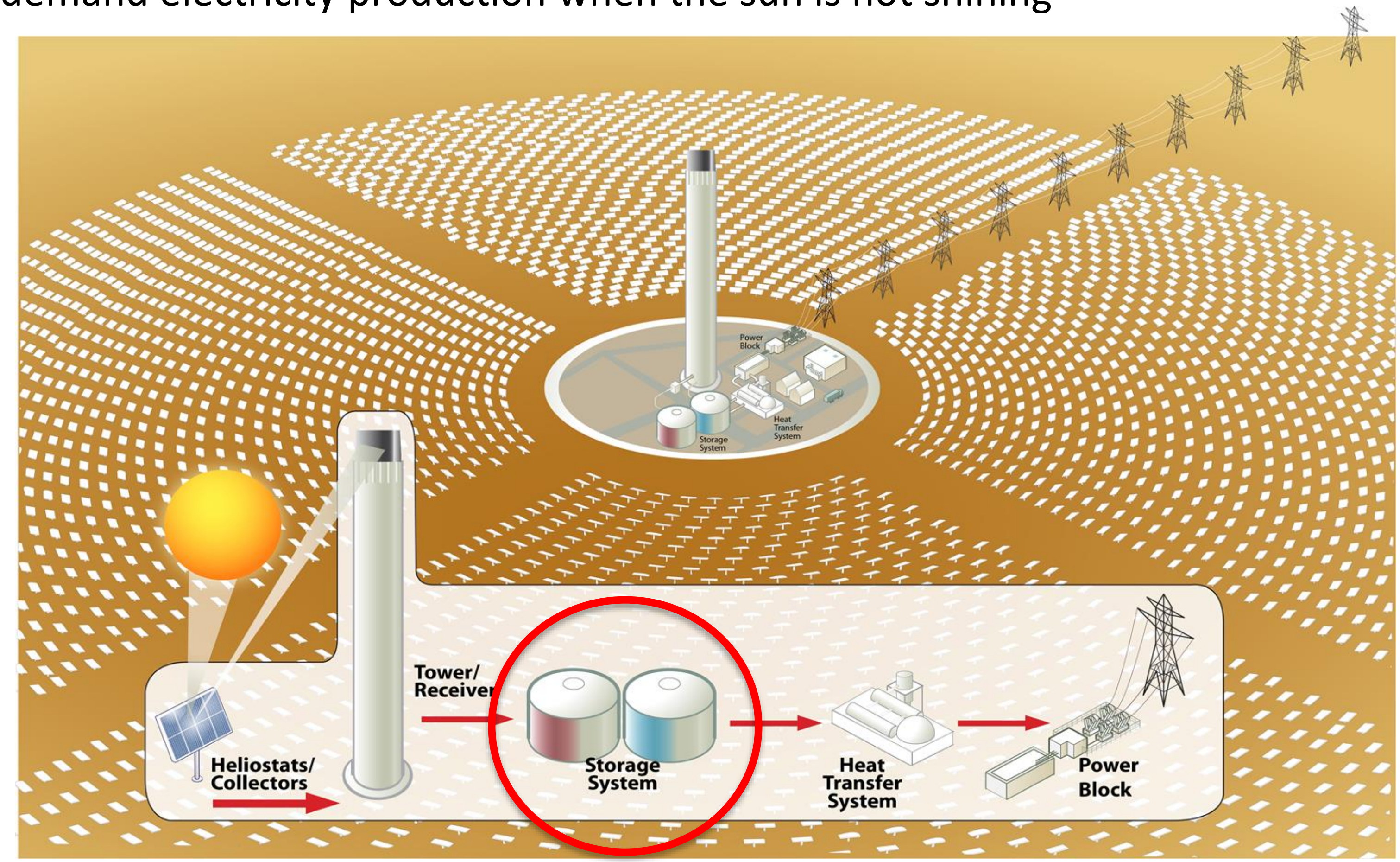




Concentrating Solar Power

CSP and Thermal Energy Storage

- Concentrating solar power uses mirrors to concentrate the sun's energy onto a receiver to provide heat to spin a turbine/generator to produce electricity
- **Hot fluid can be stored as thermal energy efficiently and inexpensively** for on-demand electricity production when the sun is not shining



Timeline of CSP Development

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Solar One and Solar Two
10 MW_e
Daggett, CA
1980’s – 1990’s

Stirling Energy Systems
1.5 MW_e, AZ, 2010

Ivanpah, steam, 377 MW_e, CA, 2014

1970’s → 1980’s – 1990’s → 2000’s → SunShot 2011 -

National Solar Thermal Test Facility
6 MW_t, Albuquerque, NM, Est. 1976

SEGS, 1980’s
9 trough plants
354 MW_e, CA

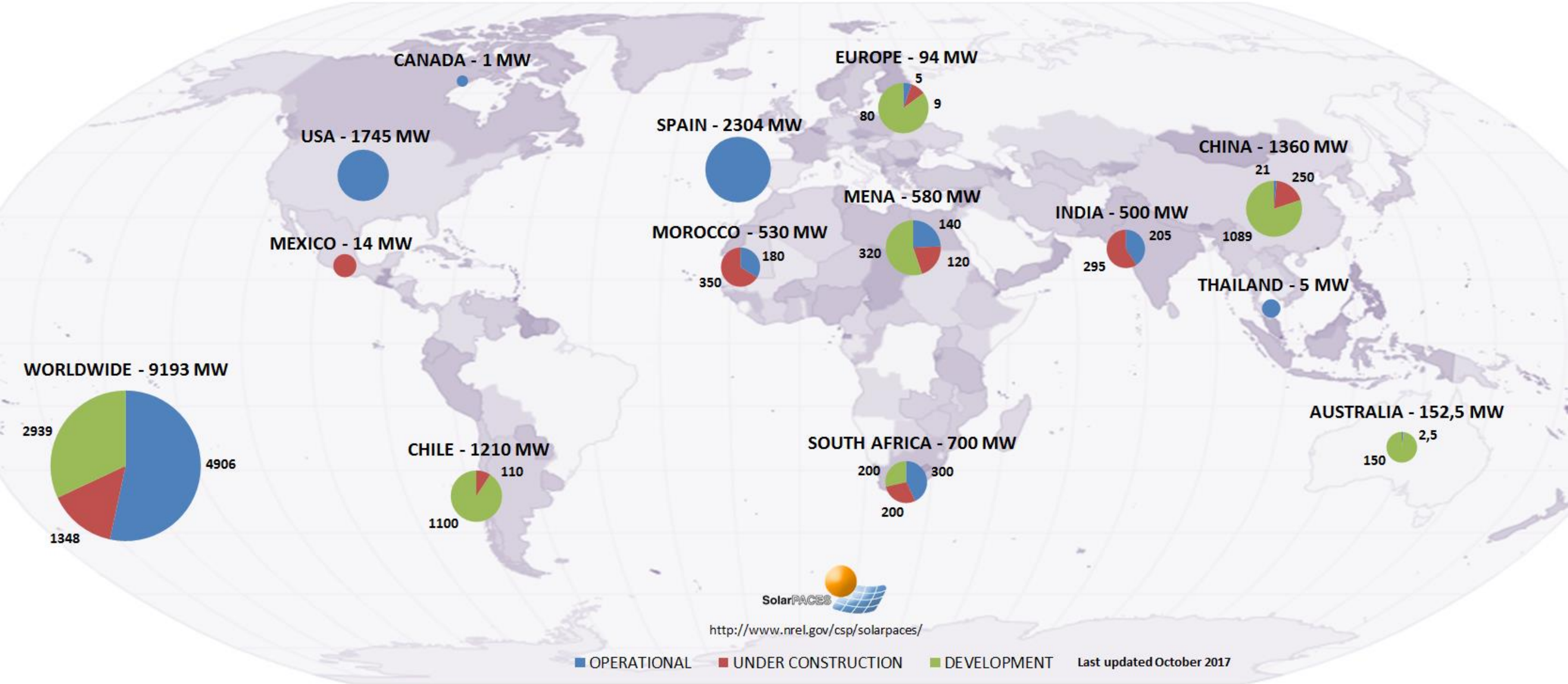
PS10/20, steam, Spain, 2007-2009

Gemasolar, molten salt, 19 MW_e, Spain, 2011

Crescent Dunes, molten salt, 110 MW_e, NV, 2015

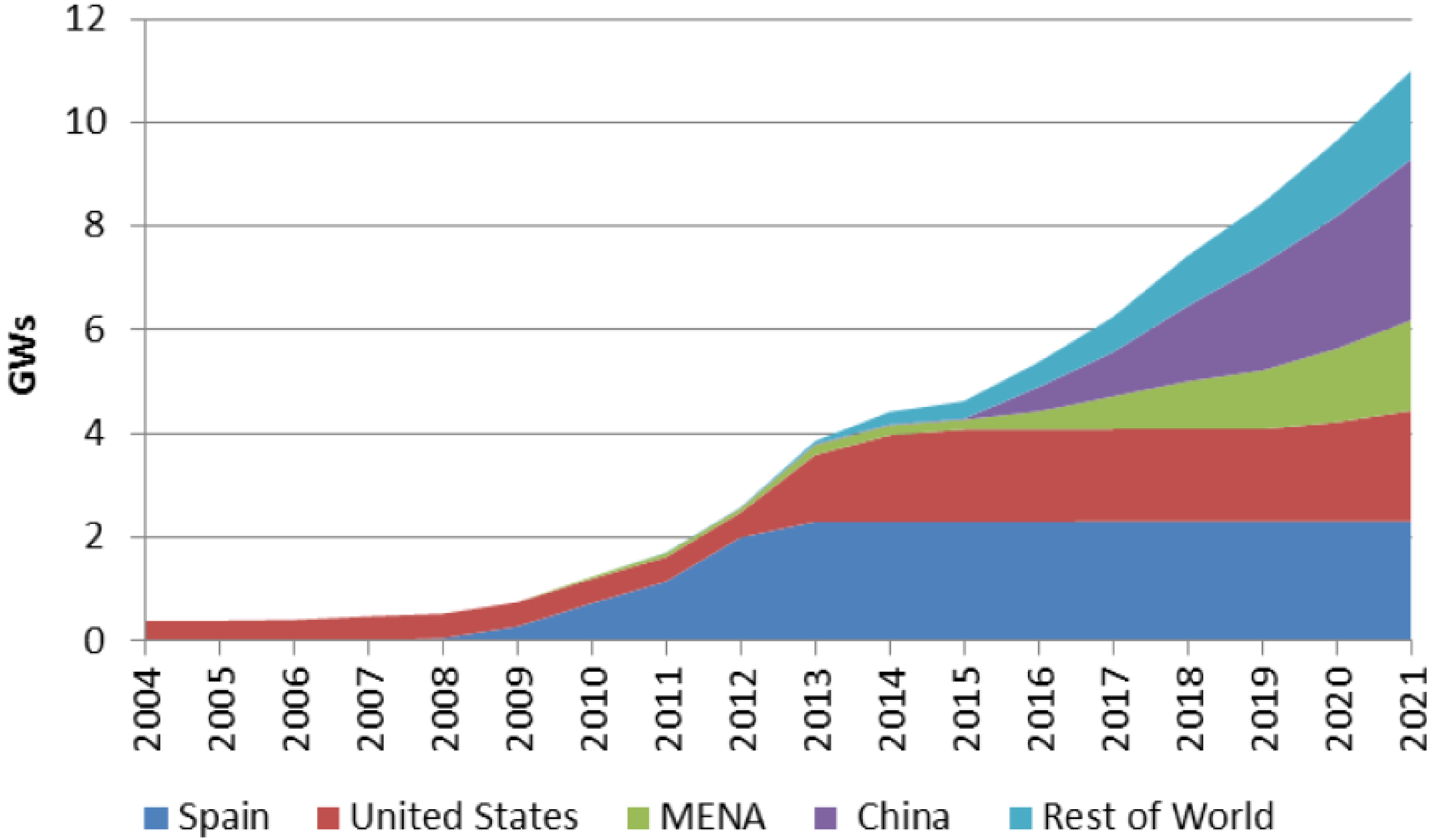
CSP Projects Around the World

Through October 2017



http://www.solarpaces.org/csp-technologies/csp-projects-around-the-world/

Actual and Projected Growth of CSP



https://www.nrel.gov/docs/fy17osti/67464.pdf

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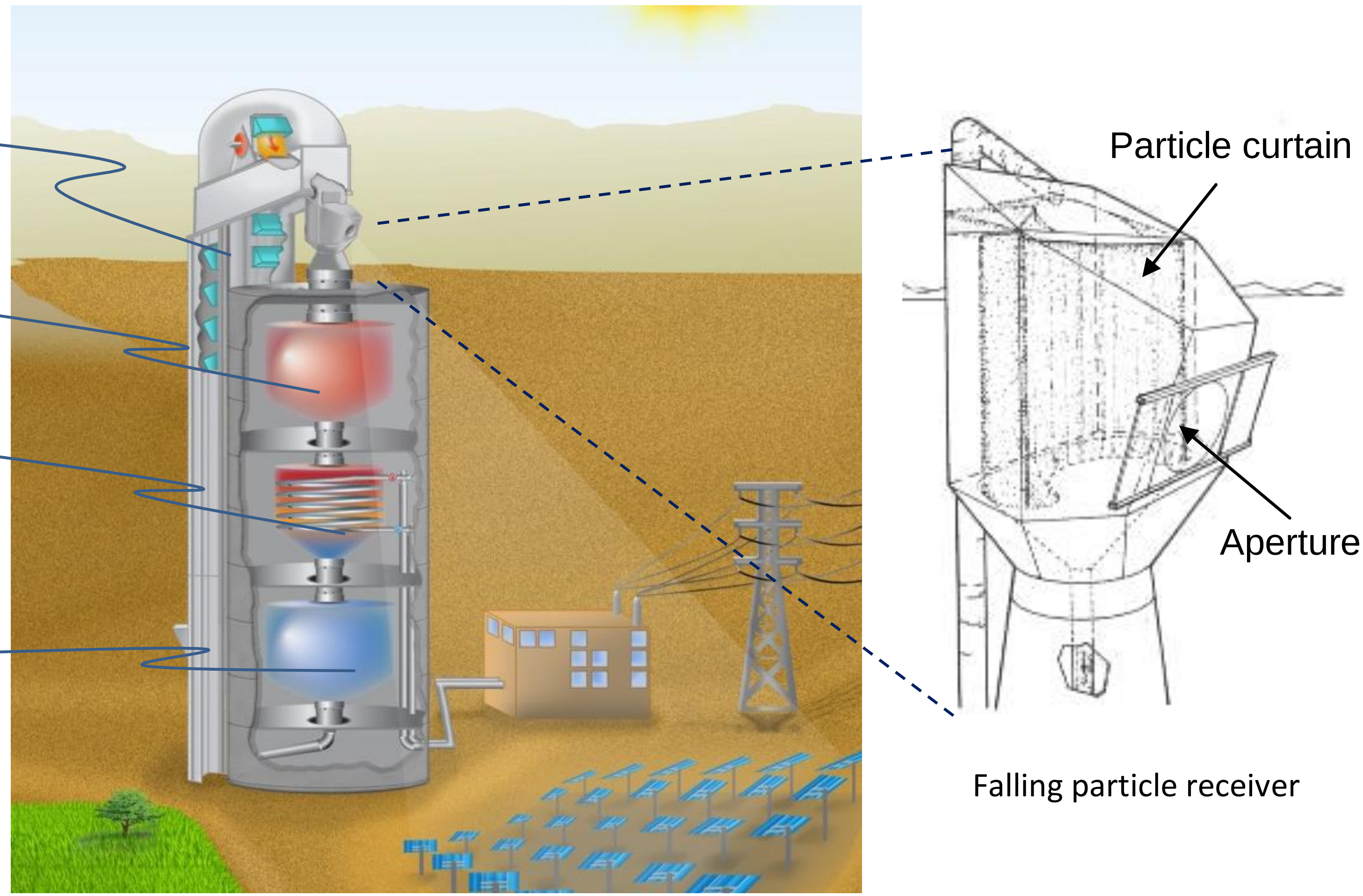
History of Particles

- Particles as a heat-transfer medium have been studied and commercialized for nearly a century
  - 1920's: First industrialized fluidized particle reactors for coal gasification
  - 1940's: First circulating fluidized bed for catalytic cracking of mineral oils and metallurgical processing
  - 1960's: First fluidized bed for combustion of coal in a power plant in Germany
  - 1980's: Particle receivers first evaluated for CSP
  - 2007: First on-sun falling-particle receiver test
  - 2015: First high-temperature (>700 C) continuously recirculating on-sun particle receiver tests
  - 2016: First fluidized-bed CSP plant in Sicily

High Temperature Falling Particle Receiver

(DOE SunShot Award FY13 – FY16)



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

Advantages of particle Power™

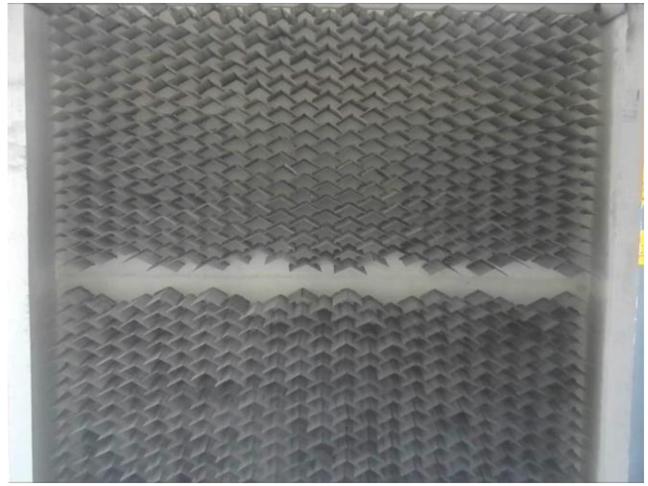
- Higher temperatures than molten salts (>1000 ˚C)
  - Enables more efficient power cycles
- Direct heating of particles vs. indirect heating of tubes
  - Higher solar fluxes for increased receiver efficiency
- No freezing or decomposition
  - Avoids costly heat tracing
- Direct storage of hot particles
  - Reduced costs without extra heat exchangers and separate storage media

N. Siegel, Bucknell U.

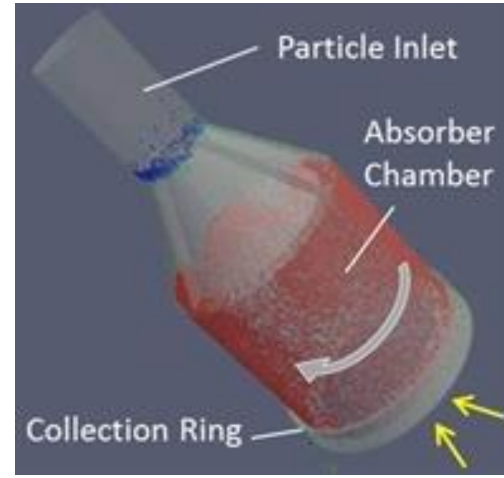
CARBO ceramic particles (“proppants”)

Alternative Particle Receiver Designs

Free-Falling (SNL)



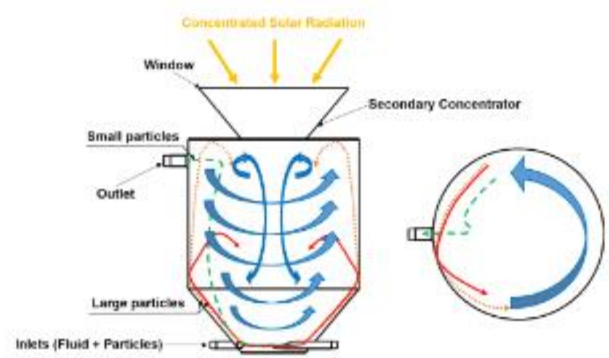
Obstructed Flow (GT, KSU)



Centrifugal (DLR)

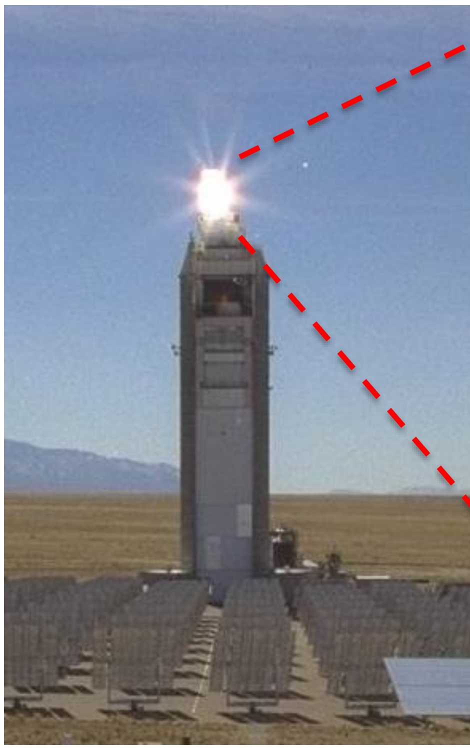
Fluidized Bed

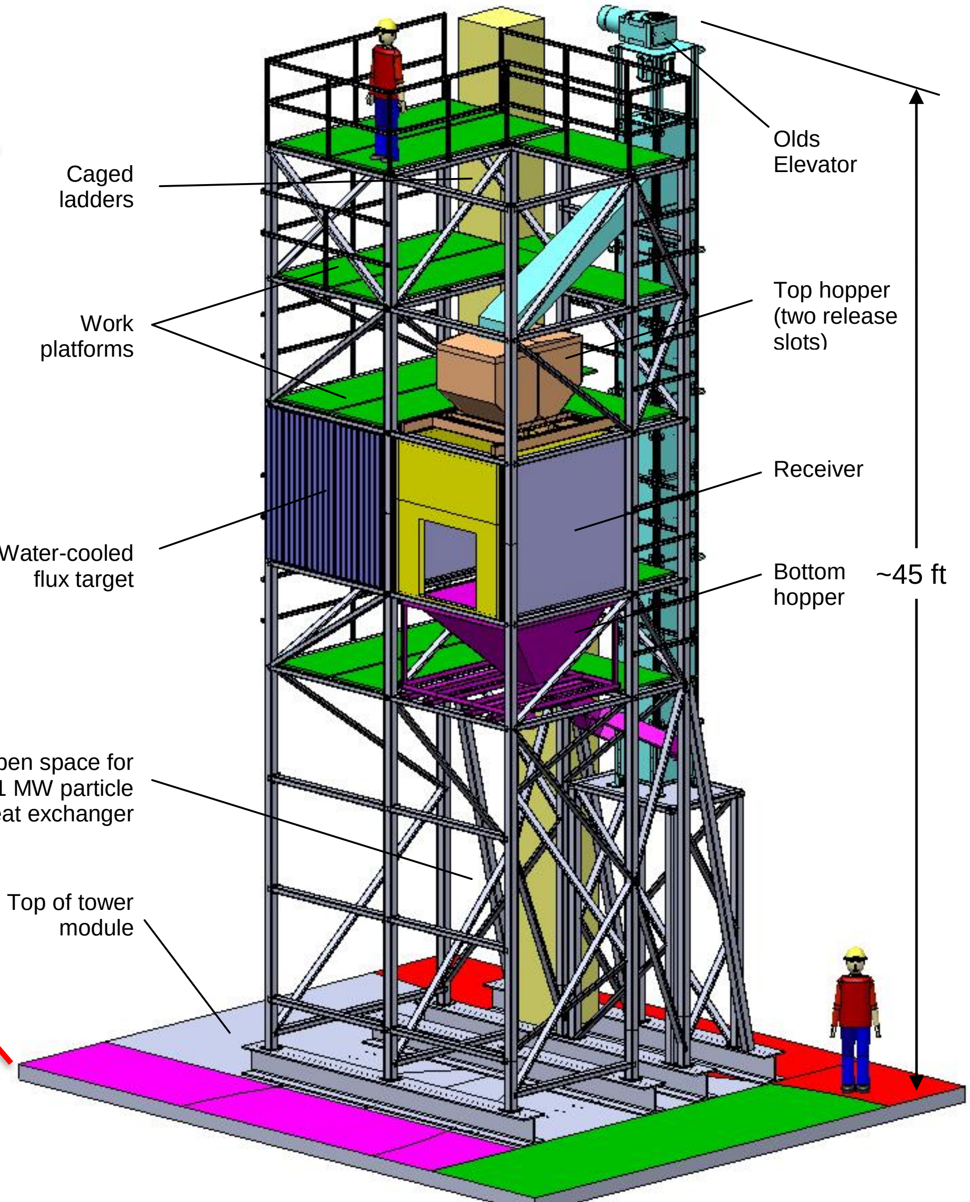
STEM – Magaldi Group



Solar Expanding Vortex Reactor, U. Adelaide

Prototype System Design

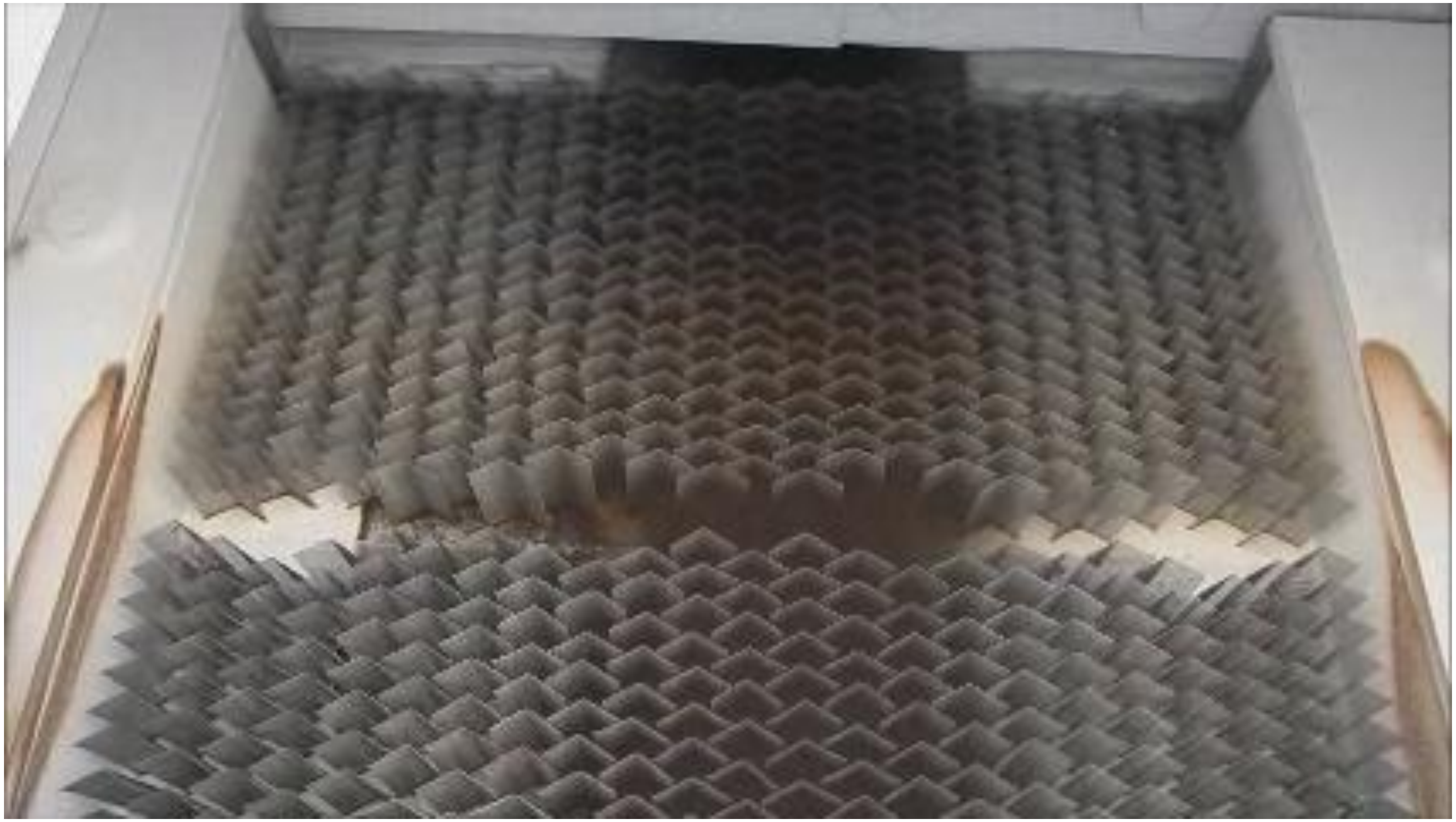




On-Sun Tower Testing

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

On-Sun Tower Testing

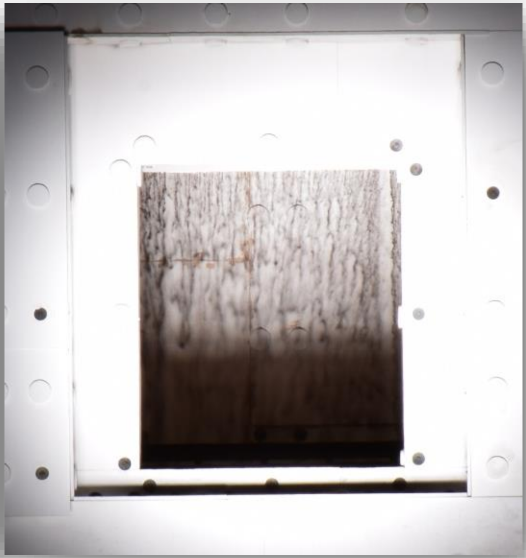


Particle Flow Through Mesh Structures
(June 25, 2015)

Results of Particle Receiver Tests

- Demonstrated continuous operation with average particle outlet temperatures > 800 ˚C
- Thermal efficiency up to ~70% to 80%
- Affordable, dispatchable (24/7) renewable energy
  - "Kill the duck"





Light Trapping with Particles?

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

16 Particle Release Patterns Tested

Zig-Zag Release

Square-Wave Release Pattern

Parallel-Line Release Pattern

Particle Light-Trapping Summary

- Simulations indicate volumetric particle release patterns (wave-like, parallel lines) can increase thermal efficiency of a particle receiver
  - Up to ~7 % at low temperatures (~100-200˚C)
  - Up to ~2-3 % at elevated temperatures (>720˚C)
  - Convective losses become significant at 720˚C
- Testing indicated that novel particle release patterns can be implemented with different discharge slot patterns



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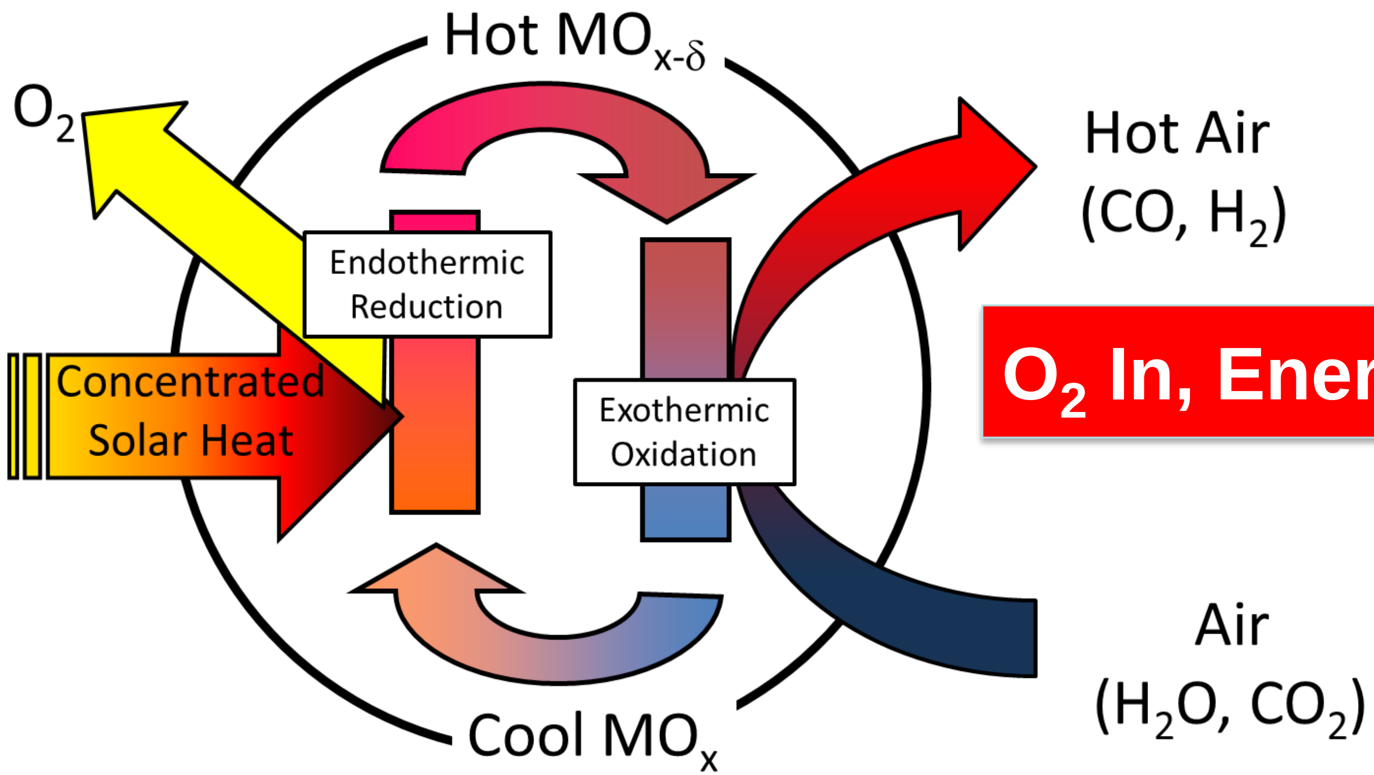
Thermochemical Particle Storage

Andrea Ambrosini & Sean Babiniec
Sandia National Laboratories

One Straightforward Solution?

Energy In, O_2 Out.



O_2 In, Energy Out

Metal Oxide Thermal Redox Chemistry

Common Demands of the Oxide

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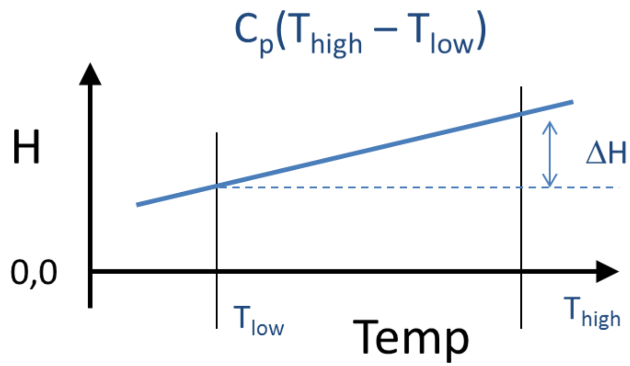
TCES	Attribute	Solar Fuels
✓	Simple, Repeatable Chemistry (No side reactions, No intermediate processing)	✓
✓	Thermodynamics Matched to Application	✓
✓	Long Term Stability – Chemical and Physical (years – 1000s if not millions of cycles)	✓
✓	Efficient volumetric/mass usage (utilization/energy density per cycle)	✓
✓	Rapid Kinetics	✓
✓	High Melting /Low Volatility/Sinter Resistant	✓
✓	Amenable to integration with receivers	✓
✓	Low Cost	✓

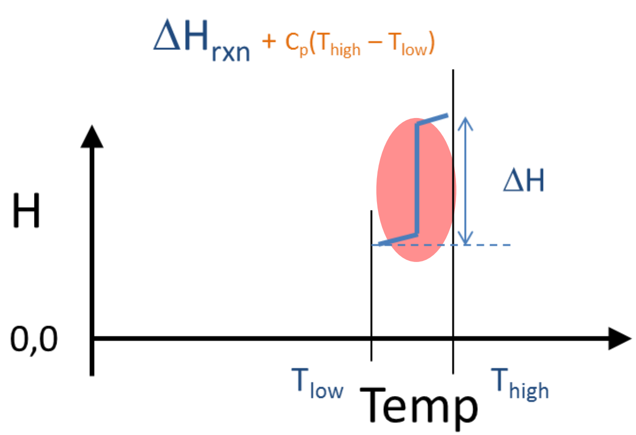
Basic Metal Oxide Thermochemical Energy Storage (TES)

$$\Delta H_{total} = \frac{\partial}{2}\Delta H_{rxn} + \bar{C}_P(T_{high} - T_{low})$$

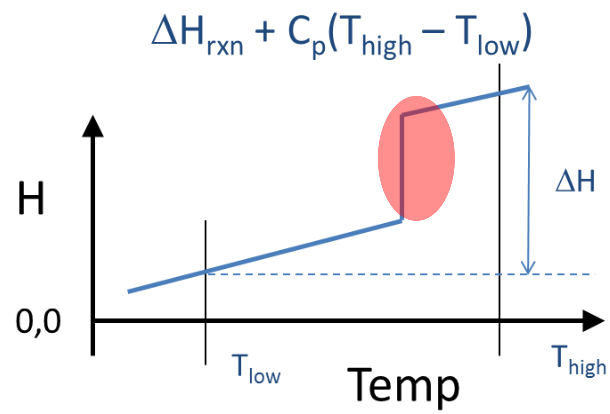
Sensible Energy Storage



Latent or Simple Chemical Energy Storage



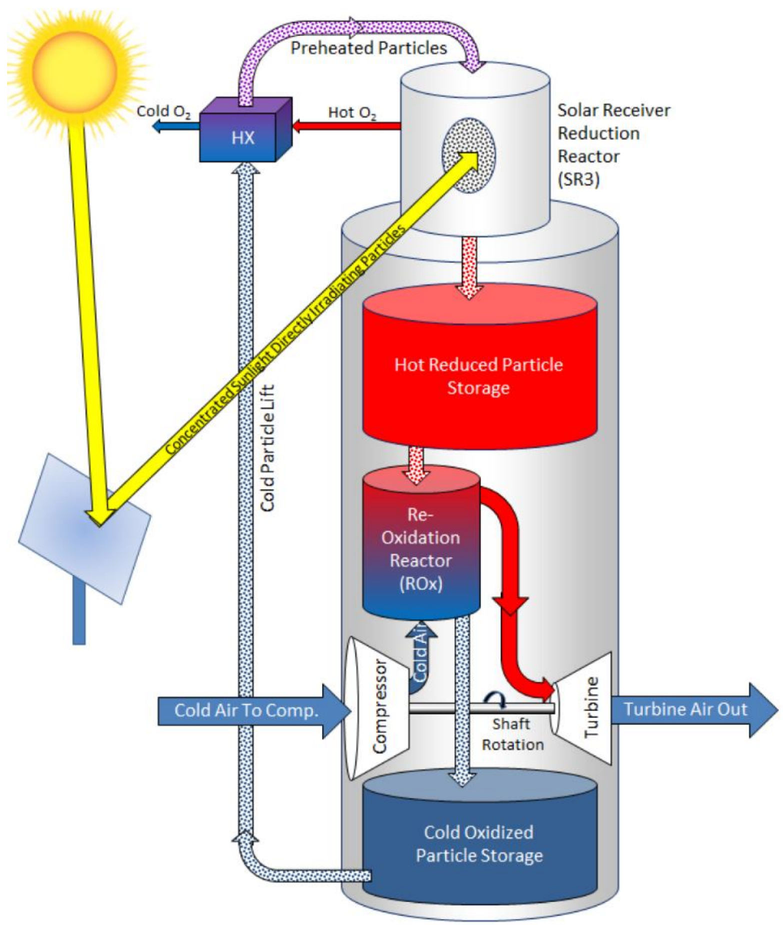
Chemical + Sensible Energy Storage



Compatible with Particle Receiver or Reactor Concepts

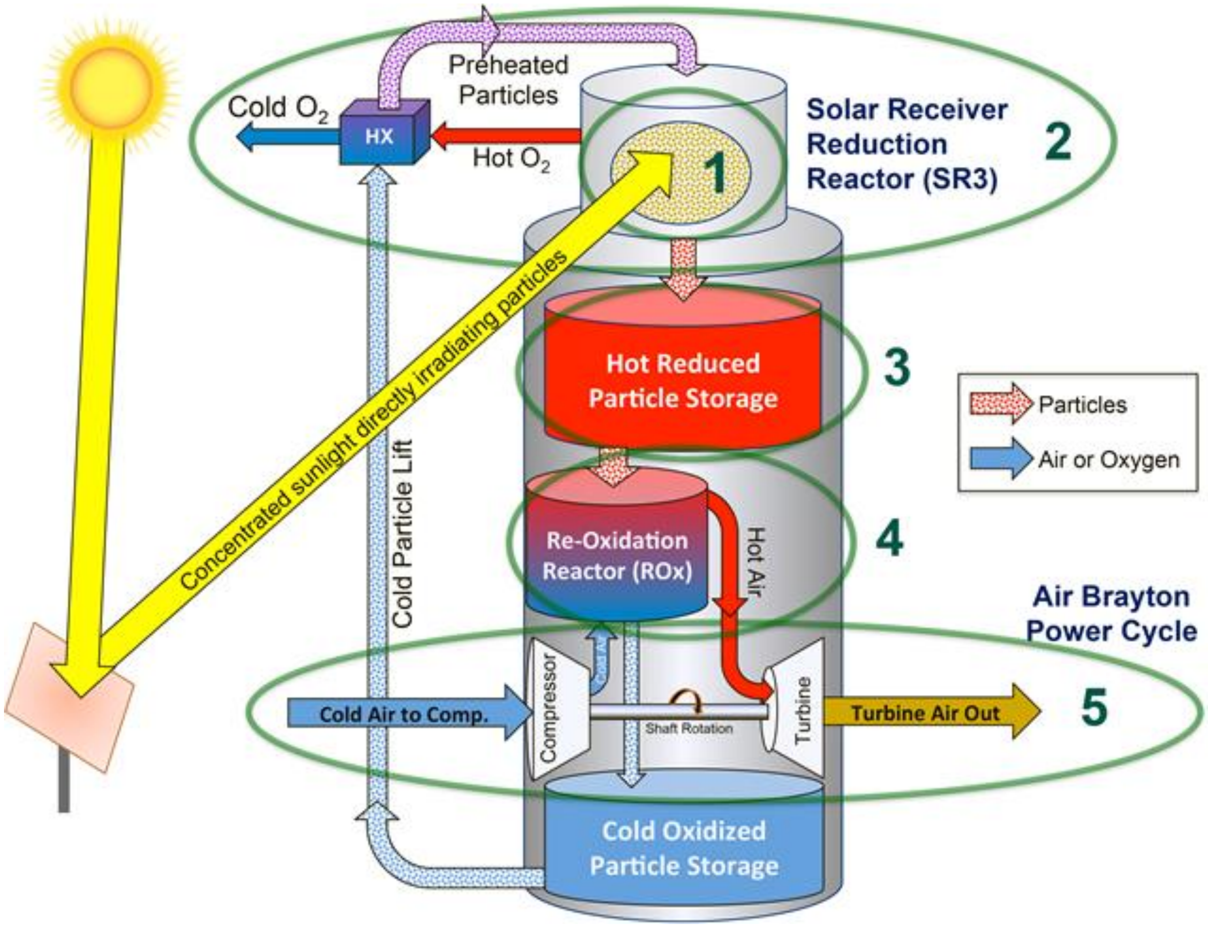
CSP: Solid particles enable efficient high-temperature turbines

- Current molten-salt systems are limited
  - Sensible-only energy storage, low energy densities
  - Salt decomposition limits turbine temperature to < 600 ° C
- Redox particle-based systems offer many advantages
  - Ability store both sensible and redox reaction enthalpy, resulting in high storage densities
    - Thermochemical energy storage (TCES)
  - Cycle is not limited by low decomposition temperatures
  - Direct irradiation of thermal storage media
  - Couples with Air-Brayton turbines
    - Re-oxidation reaction can take place directly off compressor outlet, favorably shifting thermodynamics



PROMOTES

High Performance Reduction/Oxidation Metal Oxides for Thermochemical Energy Storage



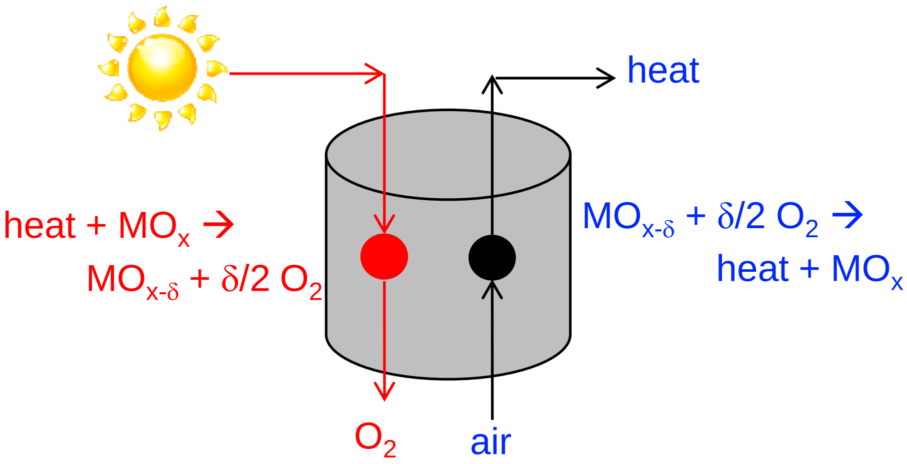
1. Materials Enabled Innovation ($\Delta H_{total} \geq 1500$ kJ/kg)
2. Solar Receiver Reduction Reactor
3. Particle Storage at T > 1000 ºC
4. Pressurized oxidation reactor Air acts as reactant and heat transfer fluid. Open cycle – no gas storage.
5. High Temp/High Efficiency Air Brayton Power Cycle.

High Performance Metal Oxides

Metal oxides are ideal materials for storage in high temperature cycles

<u>Advantages of Metal Oxides (MO):</u>

- Open or closed configurations
- Air can act as both the reactant and heat transfer fluid
- Environmentally benign
- No catalyst necessary
- No compression required for storage
- Amenable to multiple scales and temperature ranges

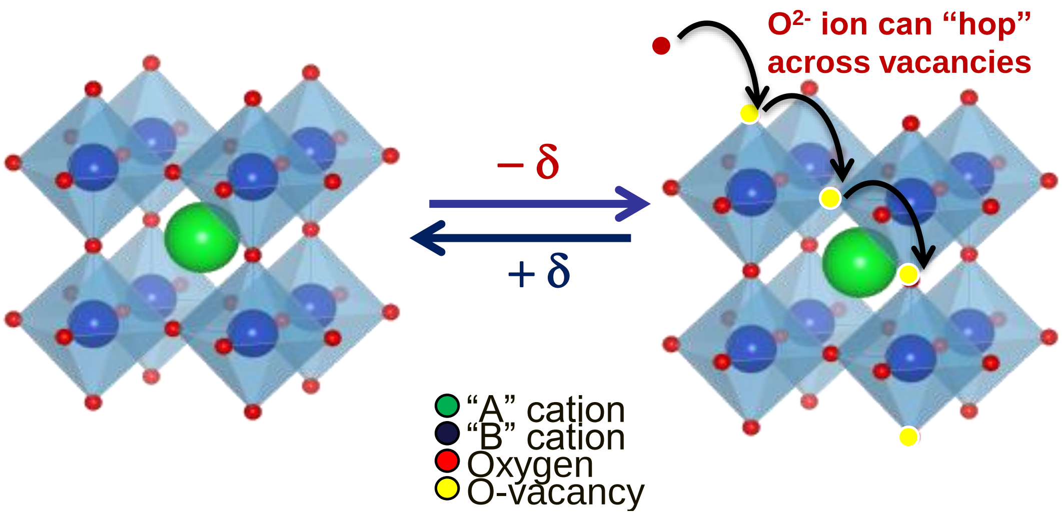


<u>Materials Concept:</u>

- Leverage both sensible heat and heat of reaction for energy storage
- Demonstrate chemical and physical stability at extreme temperatures
- Operate over a broad range of temperatures and pressures
- Develop and tailor materials properties through elegant design and manipulation of metal oxide chemistry

MIEC Perovskites

- Mixed ionic-conducting (MIEC) oxides are redox-active materials which efficiently conduct both O^{2-} and electrons
- No crystallographic phase change occurs during redox
- Vacancies facilitate oxide ion transport
- Redox activity continuous over variety of T and pO2



Parameter Space:

- Energy storage capacity, $DH_{tot} = DH_{rxn} + C_p\Delta T = 1500$ kJ/kg
- Cycling between T_H of 1000 – 1350 °C and T_L of 200 °C
- pO_2 during reduction $\geq 10^{-3}$ atm
- pO_2 during oxidation ≤ 1 atm

Total Storage Potential

$$\Delta H_{tot} = \Delta H_{rxn} + C_p \Delta T$$

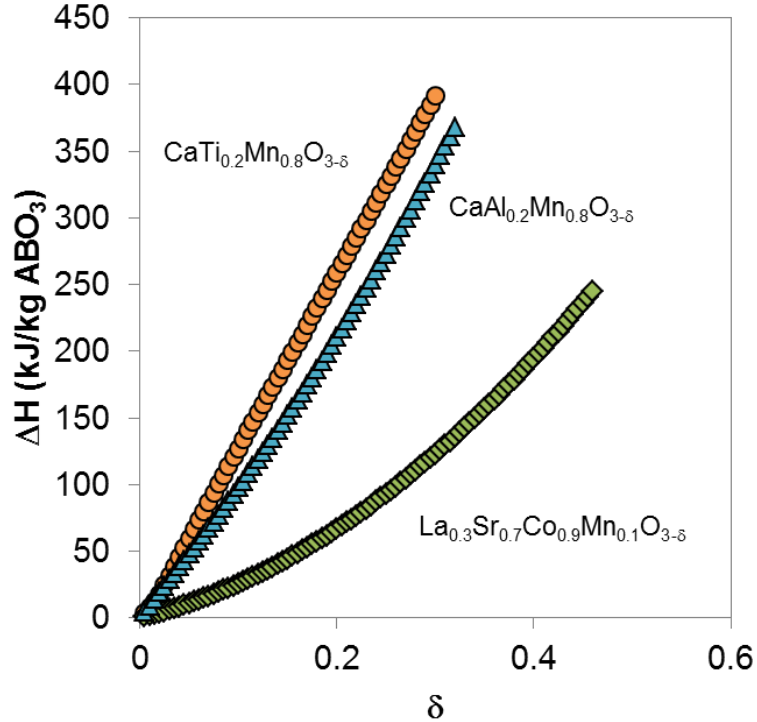
Latent heat assumes pO_2 swing of 0.001 to 0.9
Sensible heat assumes $C_p = 15R$, $T_L = 200$ °C

LSCM3791

Temperature (°C)	Sensible (kJ/kg)	Latent (kJ/kg)	Total (kJ/kg)
1100	536	192	728
1200	595	225	820
1350*	684	289*	973

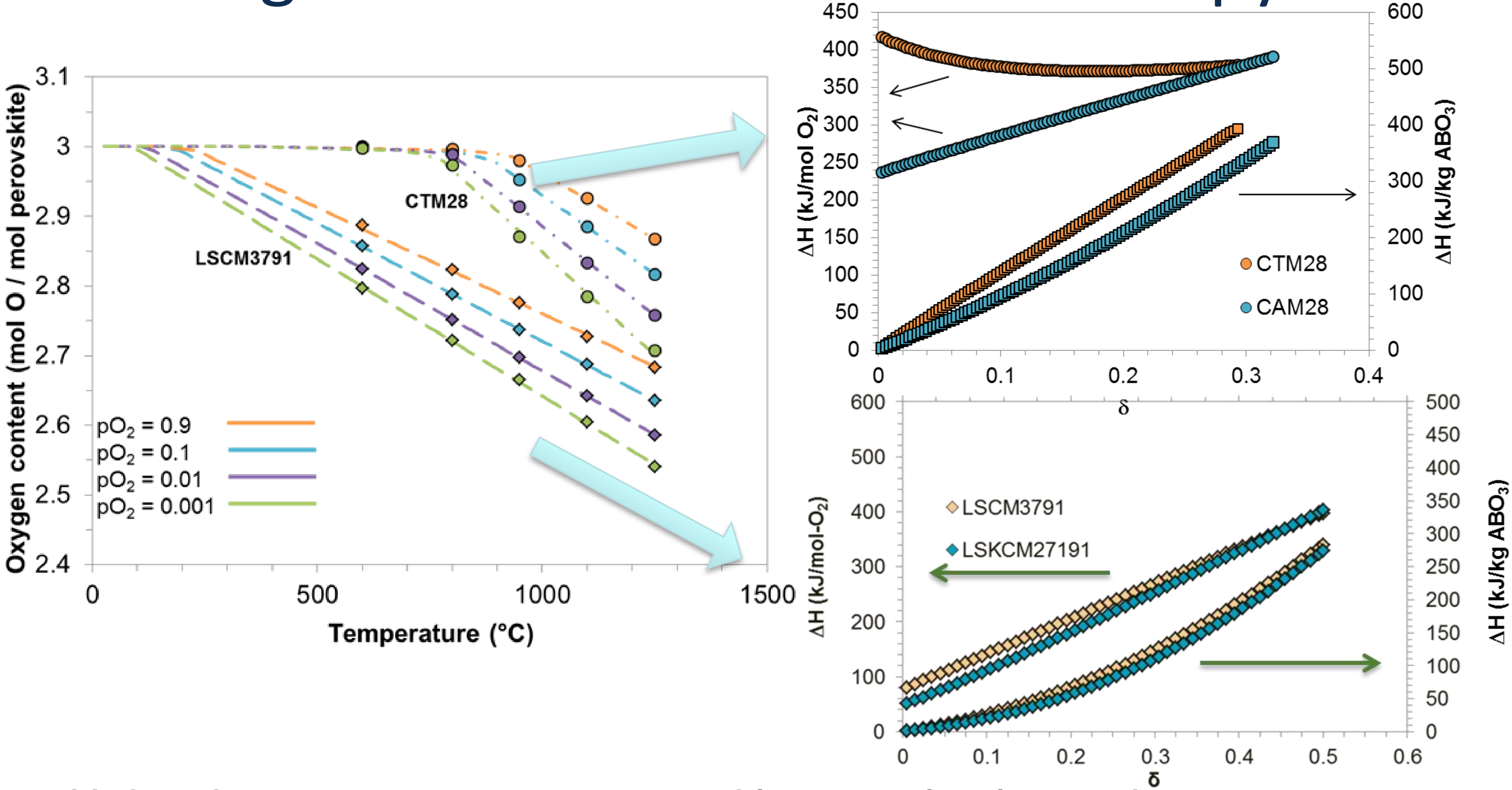
CAM28

Temperature (°C)	Sensible (kJ/kg)	Latent (kJ/kg)	Total (kJ/kg)
1100	826	293	1119
1200	918	351	1269
1350*	1056	450*	1506



*Values at 1350 °C are extrapolated from δ vs T data

Advancing the State of the Art: Balancing Reduction extent and Enthalpy



- High reduction onset temperature and lower molecular weights increase partial molar and mass specific enthalpies.
- Earth Abundant Elements manage costs.

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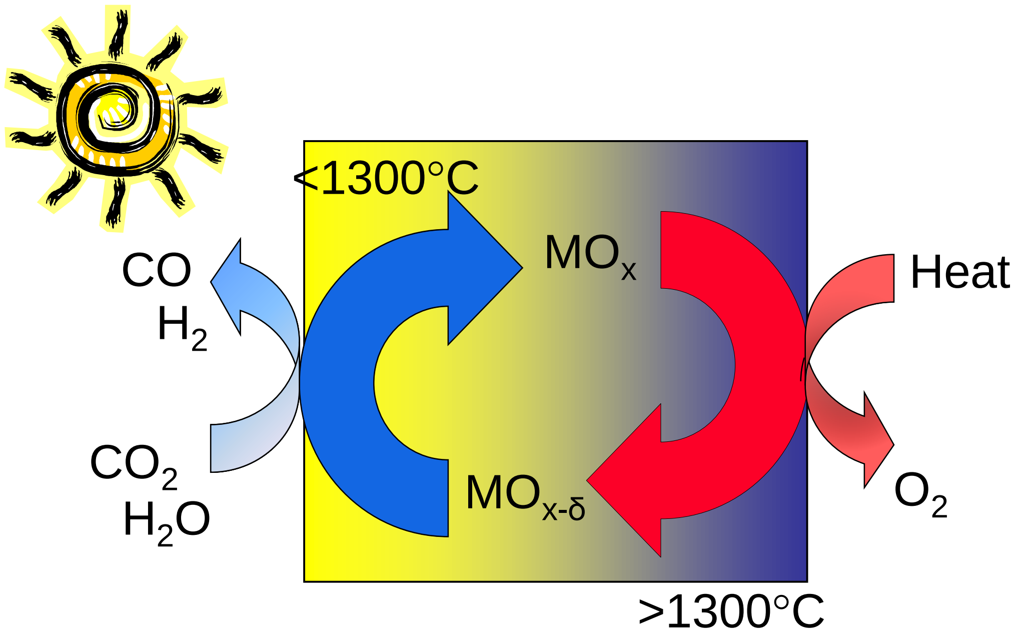
Sunshine to Petrol



Directly apply a solar energy source to effectively split CO_2 and H_2O into syn gas, utilizing redox-active metal oxides, in a process analogous to, but potentially more efficient than, photochemical or biological processes.

Two step solar-thermochemical process utilizing redox reaction to split CO_2 or H_2O:

MO_x + Sunlight → $MO_{x-\delta} + \delta/2O_2$ (Thermal Reduction)

$MO_{x-\delta} + \delta/2CO_2 \rightarrow MO_x + \delta/2CO$ (CO_2-Splitting Oxidation)

$MO_{x-\delta} + \delta H_2O \rightarrow MO_x + \delta H_2$ (H_2O-Splitting Oxidation)

Sunlight + CO_2 + H_2O → Fuel + O_2

Impact:

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Meeting a significant fraction of transportation fuel demand with solar fuels is certainly plausible!

- ***<u>High solar to fuel efficiency (>10%) is absolutely required.</u>***
  - Cost
  - Scale (land, materials of construction)
- *Water, CO_2 are not limiting –*
  - Water consumption/cost relatively low
  - High impact opportunity for CO_2.
- *Consistent with other human activities occurring over multiple decades.*

E.B. Stechel and J.E. Miller "Re-energizing CO_2 to fuels with the sun: Issues of efficiency, scale, and economics" Journal of CO_2 Utilization, 1 (2013) 28–36.

Packed Particle Bed Reactor for Solar-Thermochemical H_2 Production

Ivan Ermanoski

Sandia National Laboratories

Two-Step Thermochemical Fuel Production

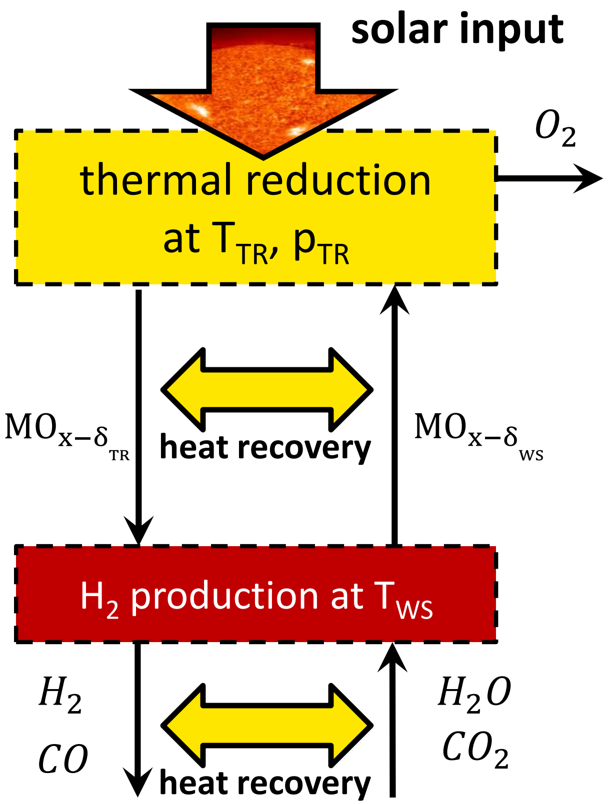
Thermal reduction

$$\frac{1}{\delta_{TR}-\delta_{WS}} MO_{x-\delta_{WS}} \rightarrow \frac{1}{\delta_{TR}-\delta_{WS}} MO_{x-\delta_{TR}} + \frac{1}{2} O_2$$

Water/CO_2 splitting

$$\frac{1}{\delta_{TR}-\delta_{WS}} MO_{x-\delta_{TR}} + H_2O \rightarrow \frac{1}{\delta_{TR}-\delta_{WS}} MO_{x-\delta_{WS}} + H_2$$

$$\frac{1}{\delta_{TR}-\delta_{WS}} MO_{x-\delta_{TR}} + CO_2 \rightarrow \frac{1}{\delta_{TR}-\delta_{WS}} MO_{x-\delta_{WS}} + CO$$



A theoretically simple process.

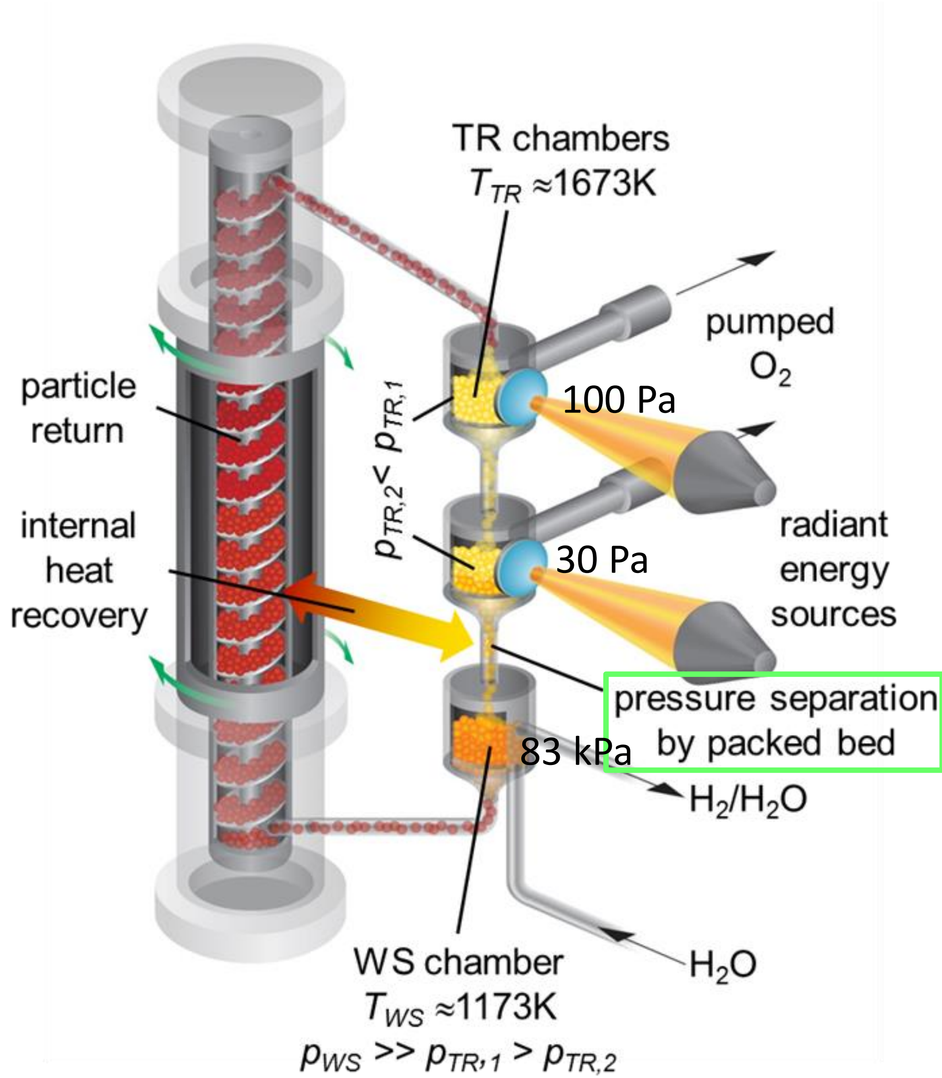
Requires low p_{O2}.

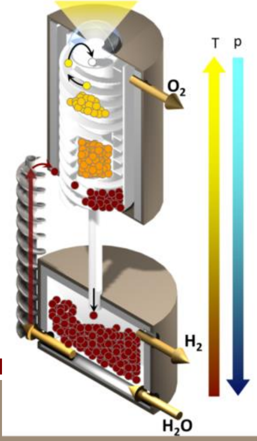
Cascading Pressure Reactor

An improvement of an earlier moving packed bed concept

- **Direct solar absorption by reactive particles**
- Internal heat recovery between T_{TR} and T_{WS}
- Continuous on-sun operation
- Temperature and product separation
- **Pressure separation by particle bed**
- Non-monolithic oxide
- Reaction kinetics decoupled from reactor operation

- Thermal reduction pressure (0.1-10Pa)
- Decreased solid-solid heat recovery requirement
- Decreased pump work requirement
- Compatibility with MW-scale plant





Cascading Pressure Reactor

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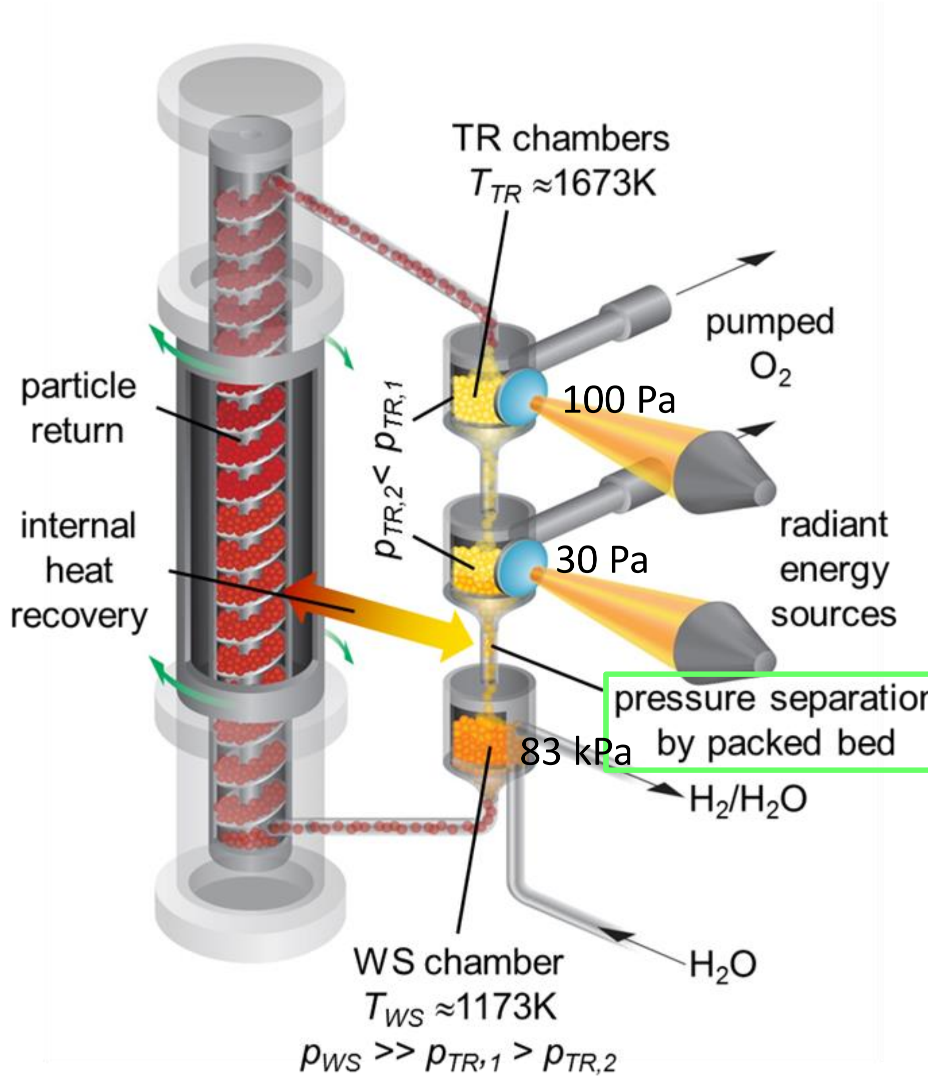
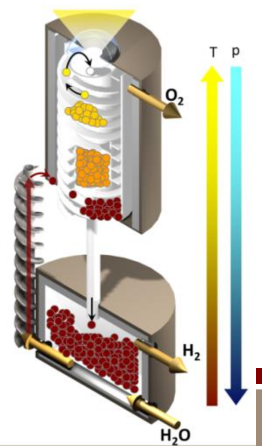
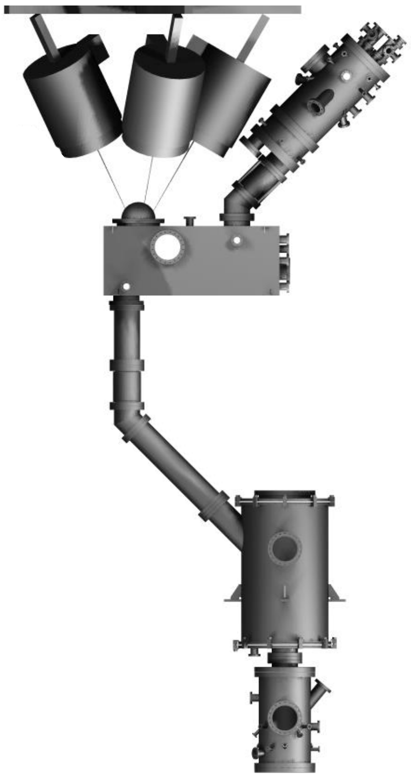
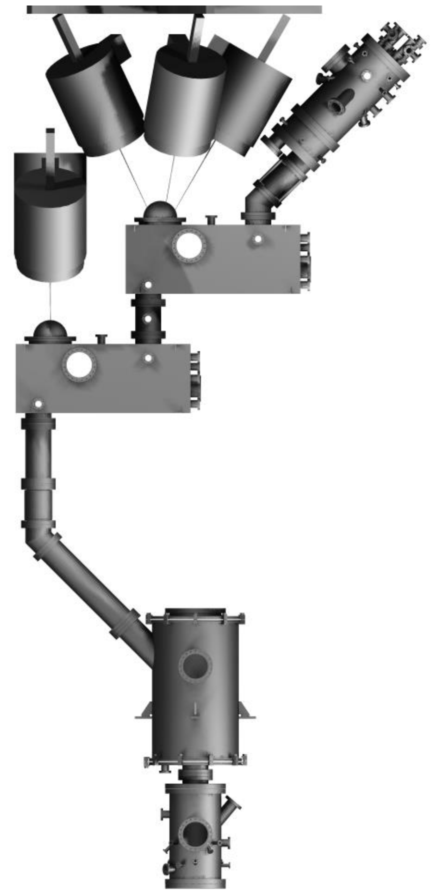




Staged Testing



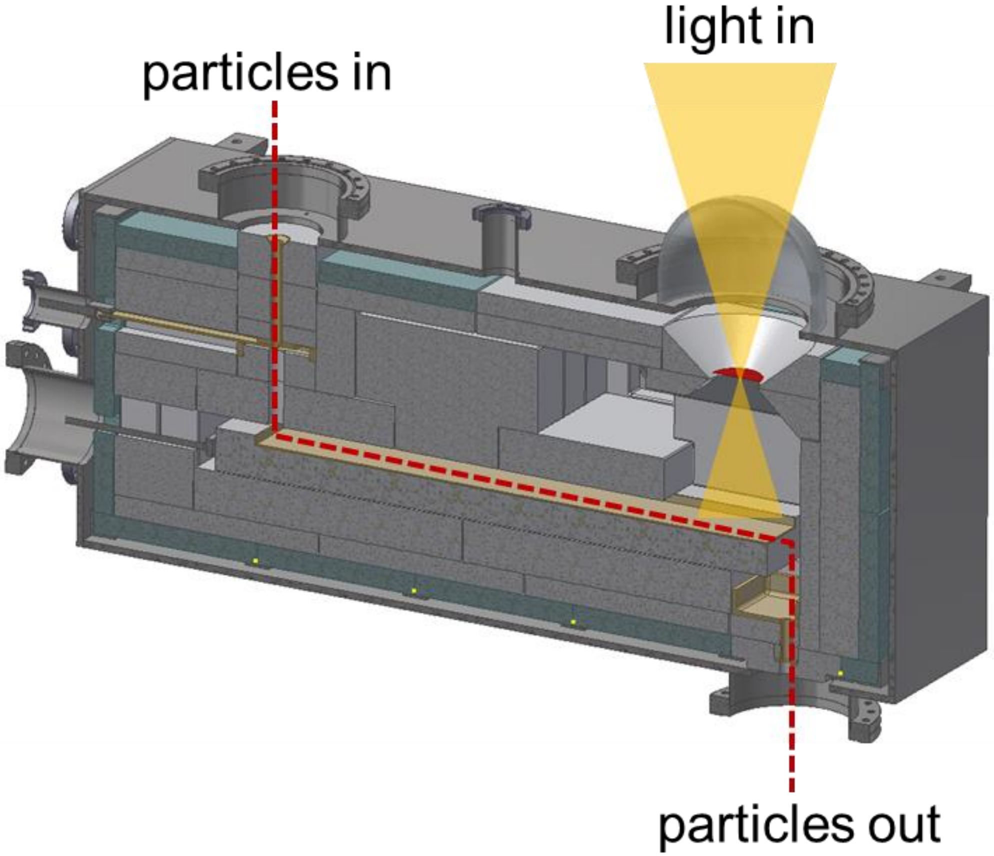
Single TR Chamber
~10 kPa Oxidation



Cascading TR Chambers
~10 kPa Oxidation

Cascading TR Chambers
Ambient Pressure Oxidation

Slip-Stick Receiver



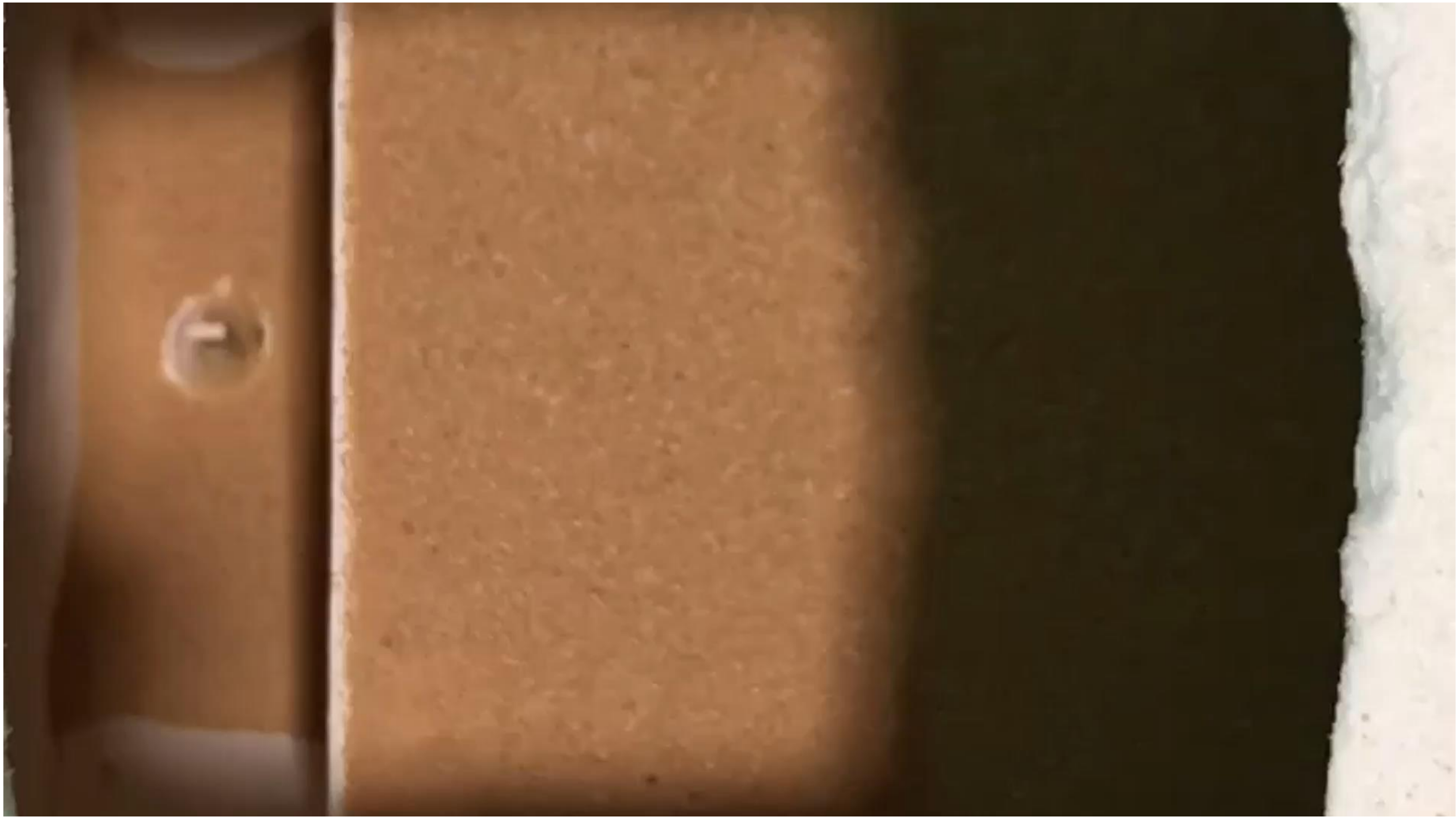
Operation:
- Rough vacuum (10^{-4} atm)
- High temperature (1500 °C)
- Refractory insulation keeps wall T<100°C
- Designed with “lift-off” dome

- Particle gate controls the flow rate onto the slip-stick plate
- Slip-stick plate motion pattern controls forward velocity/residence time

Slip-Stick Receiver Operation

Ambient particle conveying test—side view of stick-slip plate action

Slip-Stick Receiver Operation

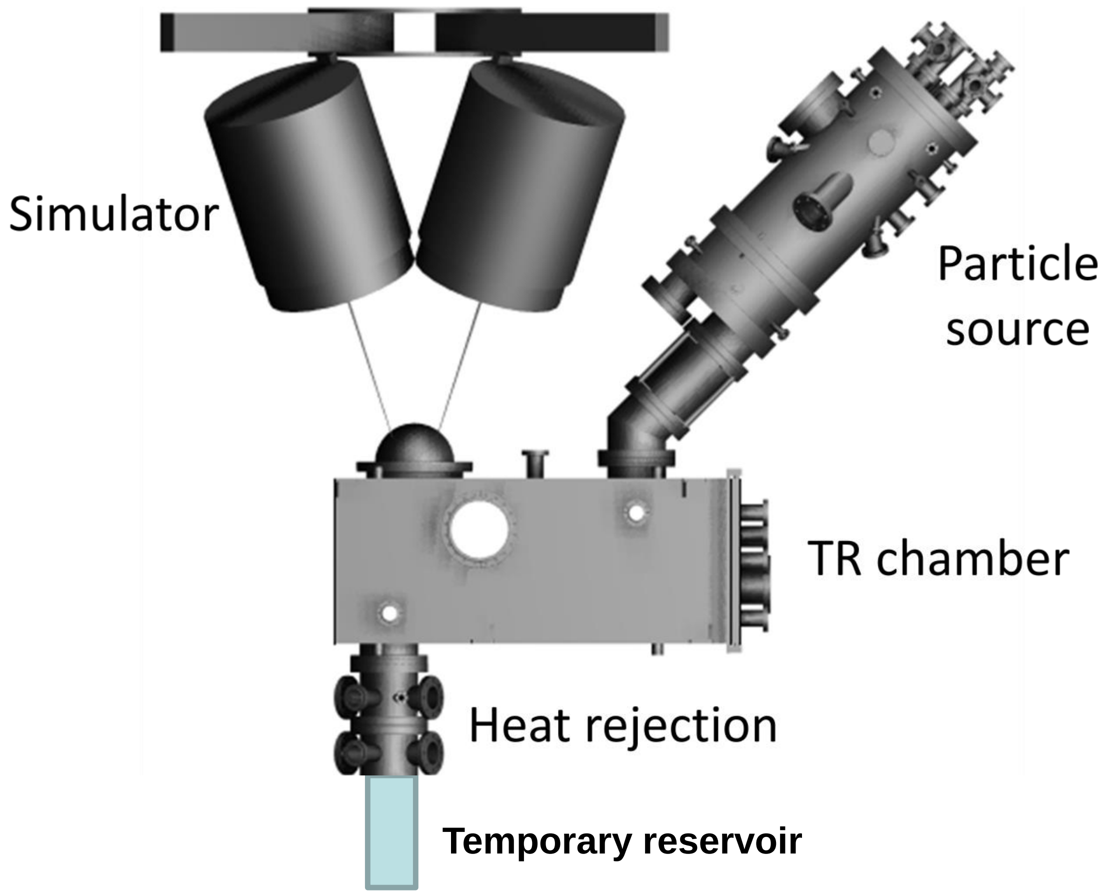


Ambient particle conveying test—view of particles moving on plate

Slip-Stick Receiver Operation

Ambient particle conveying test—particles exiting the discharge port

Partial System Test—Vacuum Reduction

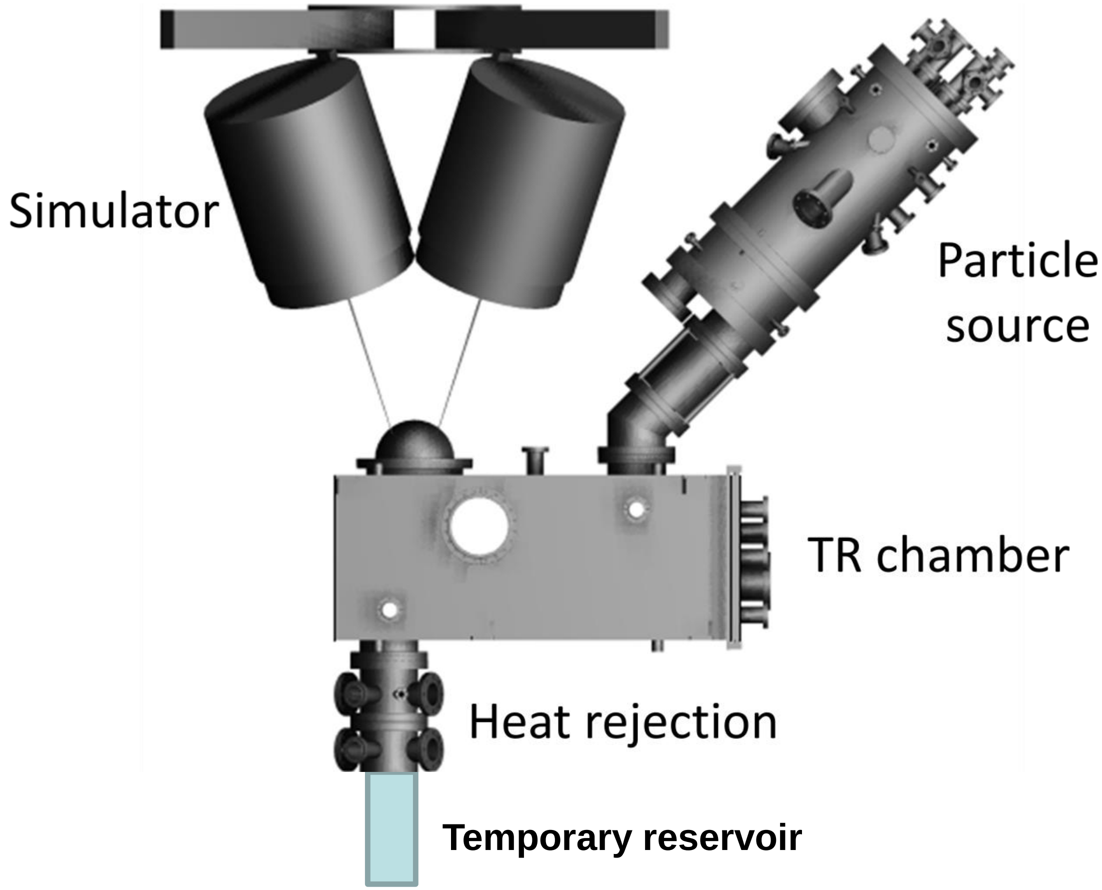


p~100 Pa

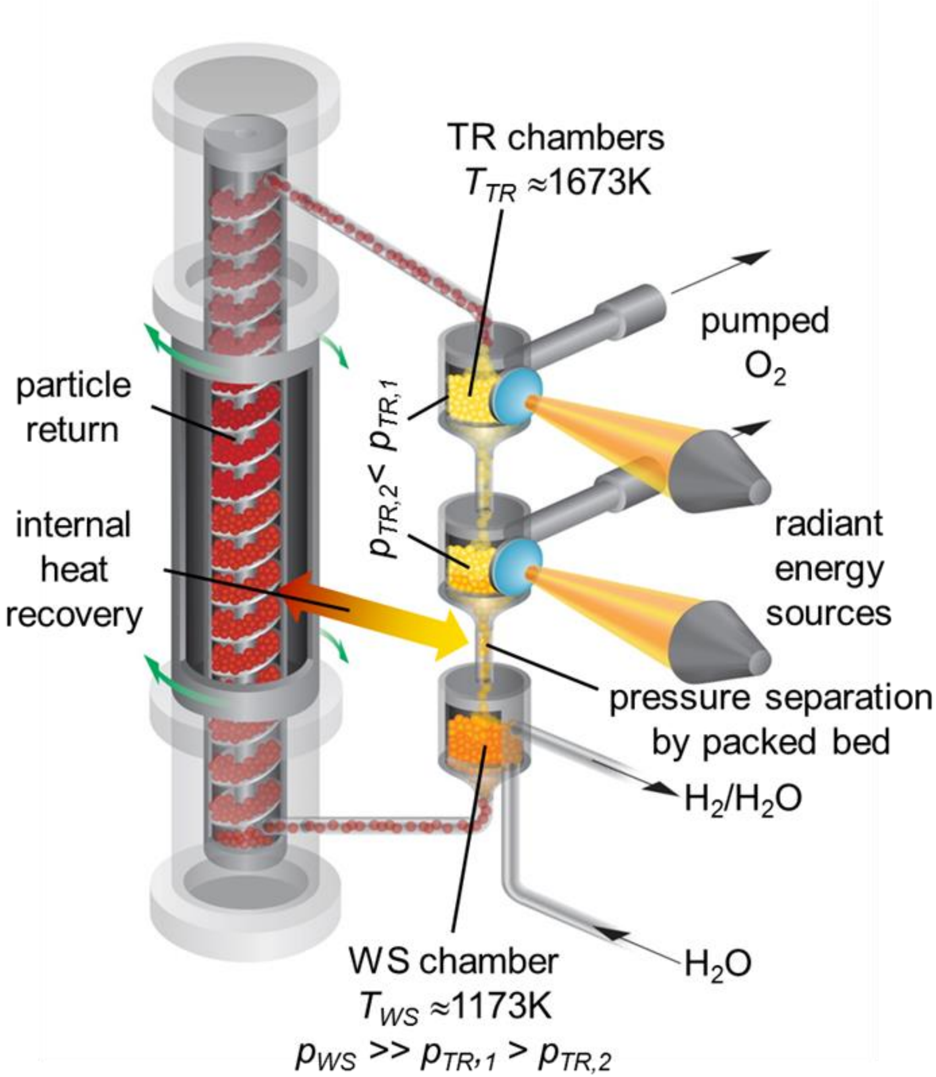
Slip-Stick Receiver Operation

Particle heating test—incandescent particles falling into temporary reservoir

Partial System Test—Vacuum Reduction



Summary and Next Steps



Overview

- Background
- Particle Research at Sandia
  - Particle Receivers for Renewable Energy
  - Thermochemical Particle Storage
  - Solar Fuel Production Using Reactive Particles
- Summary

Summary – Particle Receiver for CSP

- Advantages
  - Wide temperature range
    - No freezing; can achieve > 1000 °C
    - No trace heating
  - Direct heating of particles (high concentration ratios)
  - Direct storage of inexpensive particles
  - Particle handling/heat exchange/storage well established
- Challenges
  - Particle durability, attrition (dust emission)
  - Receiver efficiency
    - Reduce convective/radiative losses
    - Increase particle/wall heat transfer
  - Particle-to-sCO_2 heat exchanger at 700 °C, 20 MPa
  - Demonstration at larger scales (~10 – 100 MW_{th})

Summary – Thermochemical Storage and Solar Fuels

- Use of reactive particles in two-stage redox reaction for thermochemical storage or fuel production (H_2 or CO)
- Needs and Challenges:
  - Data on particle attrition
  - Better understanding of relation between particle size and heat transfer and reduction/reoxidation rates
  - Particle scale-up (manufacturing)
  - Optimized receiver design (controlled environment)
  - Technoeconomic analysis
  - Redox materials with large energy density, low cost, fast kinetics, good durability
  - Receiver design and construction: how do we realize full reduction of oxide particles in receiver (residence time, atmosphere)?

Bold Vision for Particle Power

- Particle power can address all three of our primary energy needs: electricity, heating, and fuels
  - 24/7 Low-cost electricity production
    - Falling particle receiver described in this presentation
  - Revolutionary thermochemical processes
    - Use of particle catalysts to produce nitrogen for ammonia
      - Replace energy-intensive Haber-Bosch process
    - Hydrogen production through redox particle reactions
    - Syngas production from carbon monoxide produced from CO_2 and redox particle reactions
  - Particle heating for industrial and manufacturing processes

particle Power™

Questions?

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Acknowledgments

Sandia National Laboratories

SunShot U.S. Department of Energy

arpa·e

Sandia National Laboratories

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Georgia Tech

Bucknell UNIVERSITY

SolAero TECHNOLOGIES

Australian National University

CSIRO

جامعة الملك سعود King Saud University

DLR

Acknowledgments

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- **Sandia National Labs**
  - Josh Christian, Daniel Ray, JJ Kelton, Kye Chisman, Bill Kolb, Ryan Anderson, Ron Briggs
- **Georgia Tech**
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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

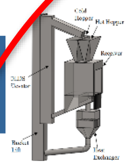
BACKUP SLIDES

Task Structure and Approach

Sandia National Laboratories

High Temperature Falling Particle Receiver

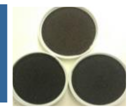
FY13: Evaluate alternative designs and concepts to meet SunShot targets
FY14: Construct on-sun prototype capable of 700 C particle temperature
FY15: On-sun testing of free-fall vs. discrete porous structures



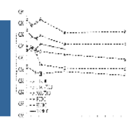
1. Receiver

1.1 – 1.2 Free-Falling Designs
- Sandia

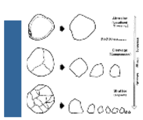
1.3 Discrete-Porous Structure Designs
- Sandia, Georgia Tech



2. Particles



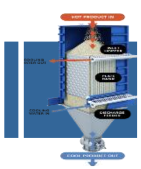
2.1 Radiative Properties
- Bucknell, Sandia



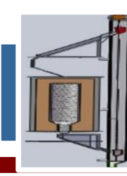
2.2 Durability
- Georgia Tech, DLR, Sandia

3. Balance of System

3.1 Thermal Storage Bin
- King Saud University



3.2 Particle/Fluid Heat Exchanger
- Georgia Tech



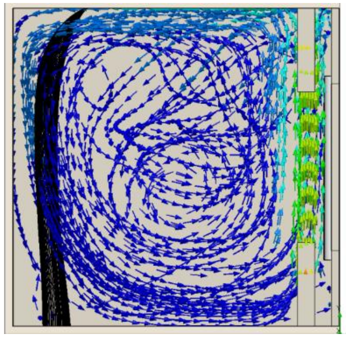
3.3 Particle Lift System
- Georgia Tech, DLR, Sandia

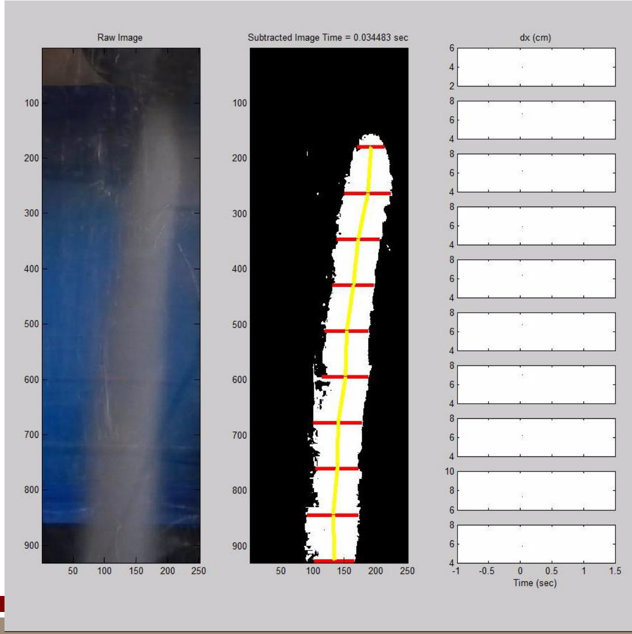
Phase I

Free-Falling Particle Receiver

Review of Phase I Findings

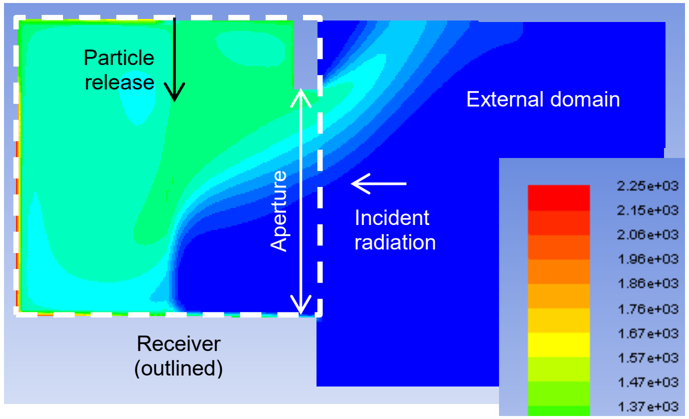
- Unheated particle flow modeling and tests
  - Optimal particle size / flow stability
  - Particle loss
  - Effect of air curtain
- Publications
  - Ho, C.K. and J.M. Christian, “Modeling Air Recirculation for High-Temperature Falling Particle Receivers,” *ASME 2013 7th International Conference on Energy Sustainability*, Minneapolis, MN, July 14-19, 2013.
  - Ho, C.K., J.M. Christian, A.C. Moya, J. Taylor, D. Ray, and J. Kelton, 2014, “ Experimental and Numerical Studies of Air Curtains for Falling particle Receivers, ES-FuelCell2014-6632, in Proceedings of ASME 2014 8th International Conference on Energy Sustainability, Boston, MA, June 29 – July 2, 2014.

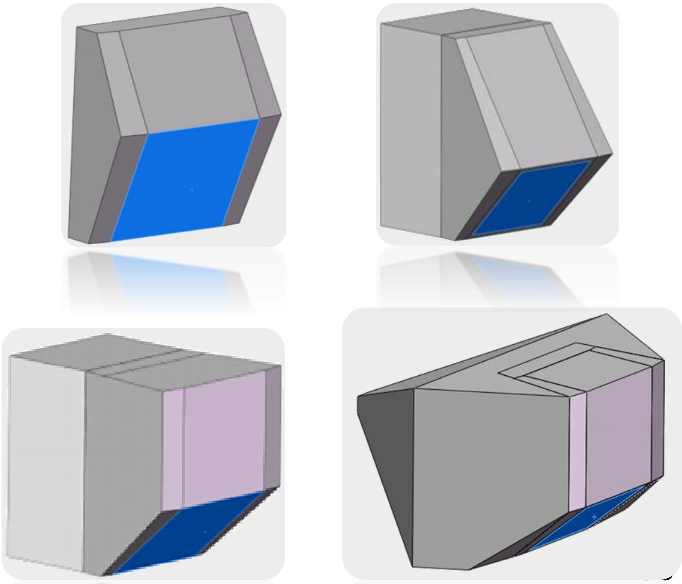




Review of Phase I Findings

- Modeling of free-falling designs
  - Particle recirculation
  - Heating with air curtain
  - Commercial designs

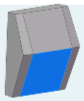
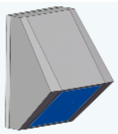
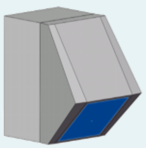
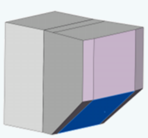
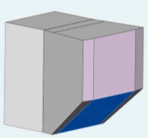
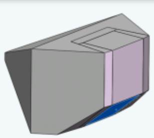
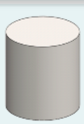




- Publications
  - Ho, C.K., J. Christian, D. Gill, A. Moya, S. Jeter, S. Abdel-Khalik, D. Sadowski, N. Siegel, H. Al-Ansary, L. Amsbeck, B. Gobereit, and R. Buck, 2014, Technology advancements for next generation falling particle receivers, *Energy Procedia*, 49, 398 - 407.
  - Christian, J.M. and C.K. Ho, 2014, Alternative Designs of a High Efficiency, North-Facing, Solid Particle Receiver, *Energy Procedia*, 49, 314 - 323.

Commercial-Scale CFD Modeling Results

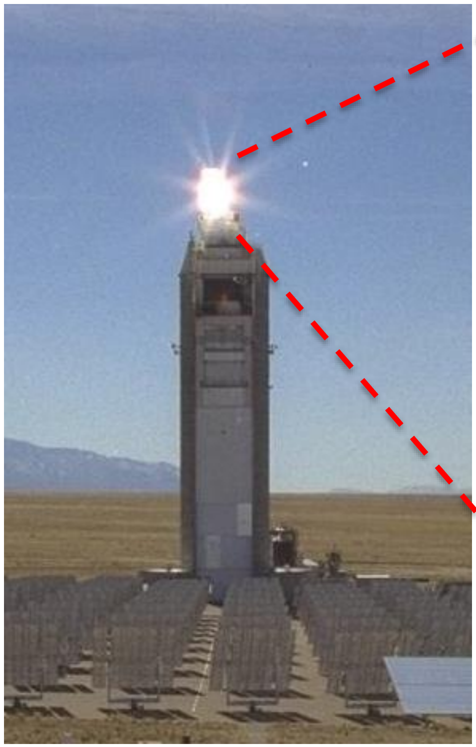
Sandia National Laboratories

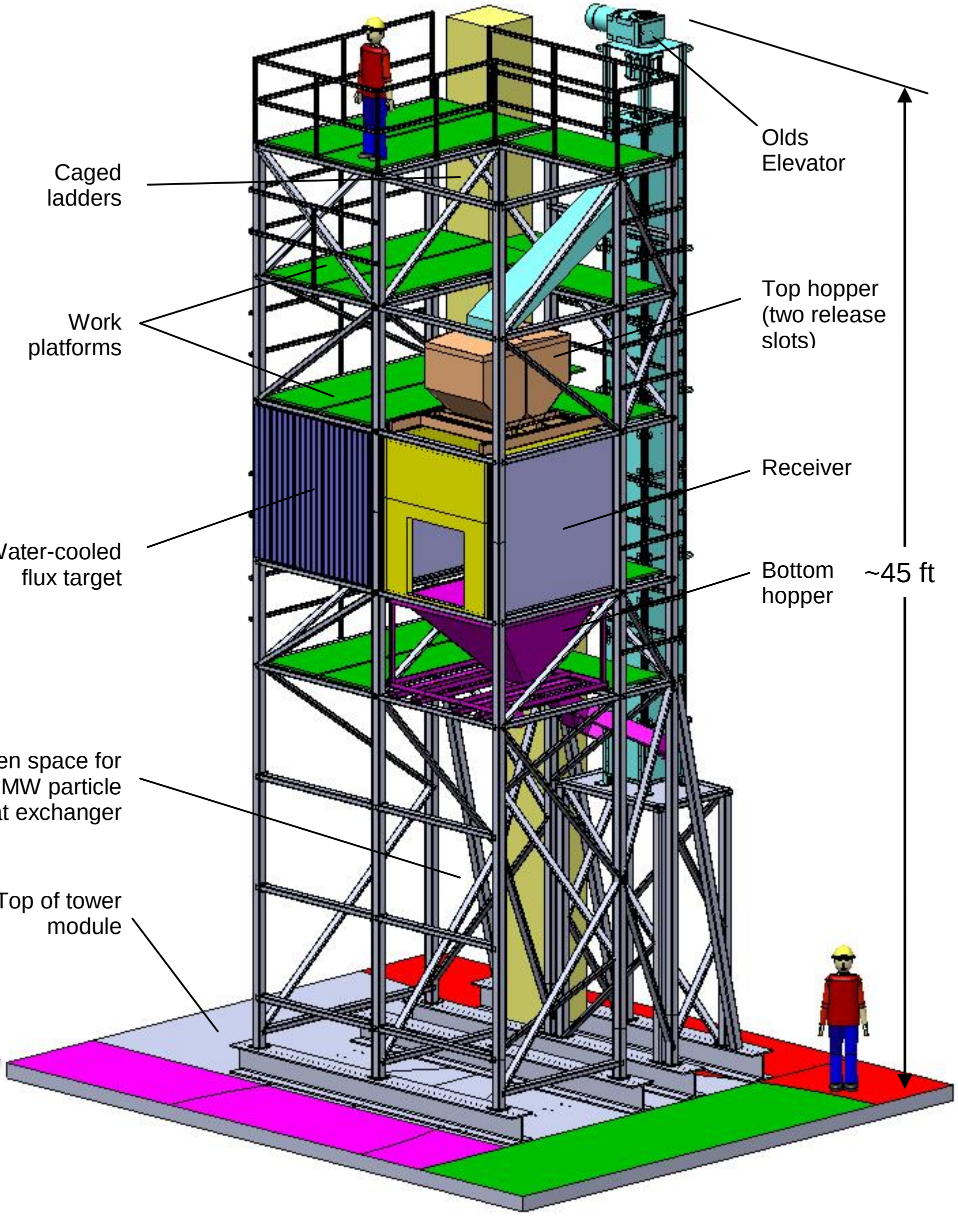
Image	Design	Thermal Efficiency (%)	Radiative Loss (%)	Convective Loss (%)	Particle Outlet Temperature (^{0}C)
	Baseline Receiver, 20^0 nod angle, height = 29 m, aperture is 17 m x 17 m	80.8	9.09	11.1	875
	Increased ceiling slope angle, 50^0 nod angle, **height = 20 m,** aperture is 10.63 m x 10.63 m	68.8	7.45	22.8	651
	Increased ceiling slope angle, 50^0 nod angle, height = 20 m, aperture is 10.63 m x 10.63 m, **extended back wall by 10 m, Particle Injection Location translated 1m back**	41.3 (large amount of particles lost through aperture)	7.18	7.96	913
	Vertical Forehead, 50^0 nod angle, height = 20 m, aperture is 10.63 m x 10.63 m, **extended back wall by 10 m, Particle Injection Location translated 2m back**	89.7	5.93	4.35	745
	Vertical Forehead, 50^0 nod angle, height = 20 m, aperture is 10.63 m x 10.63 m, **extended back wall by 10 m, particle injection location translated 2m back, *particle init. temp = 227^{o}C***	90.4	5.80	3.79	699
	Vertical Forehead, 50^0 nod angle, height = 20 m, aperture is 10.63 m x 10.63 m, **Pyramid shaped back,** Particle Injection Location translated 2m back	90.2	4.88	4.95	769
	Face Down Receiver, aperture is parallel with ground, aperture diameter = 22.1 m, height = 21.5 m, {Gobereit, 2012}	92	4.8	~3	760-780

Phase 2

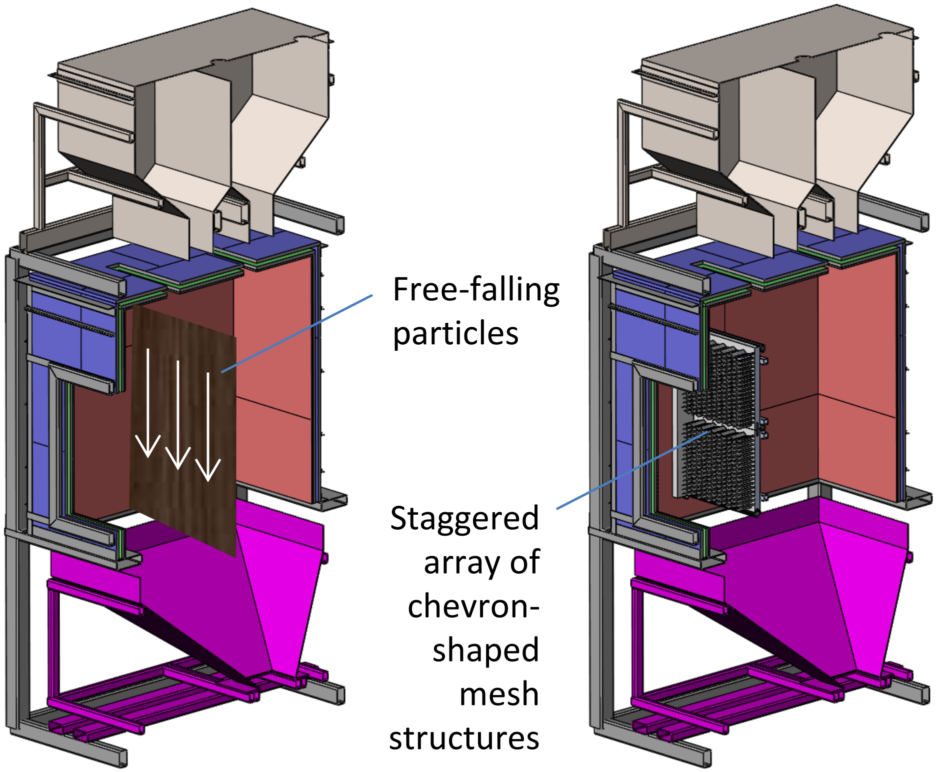
On-Sun Prototype Design and Construction

Prototype System Design



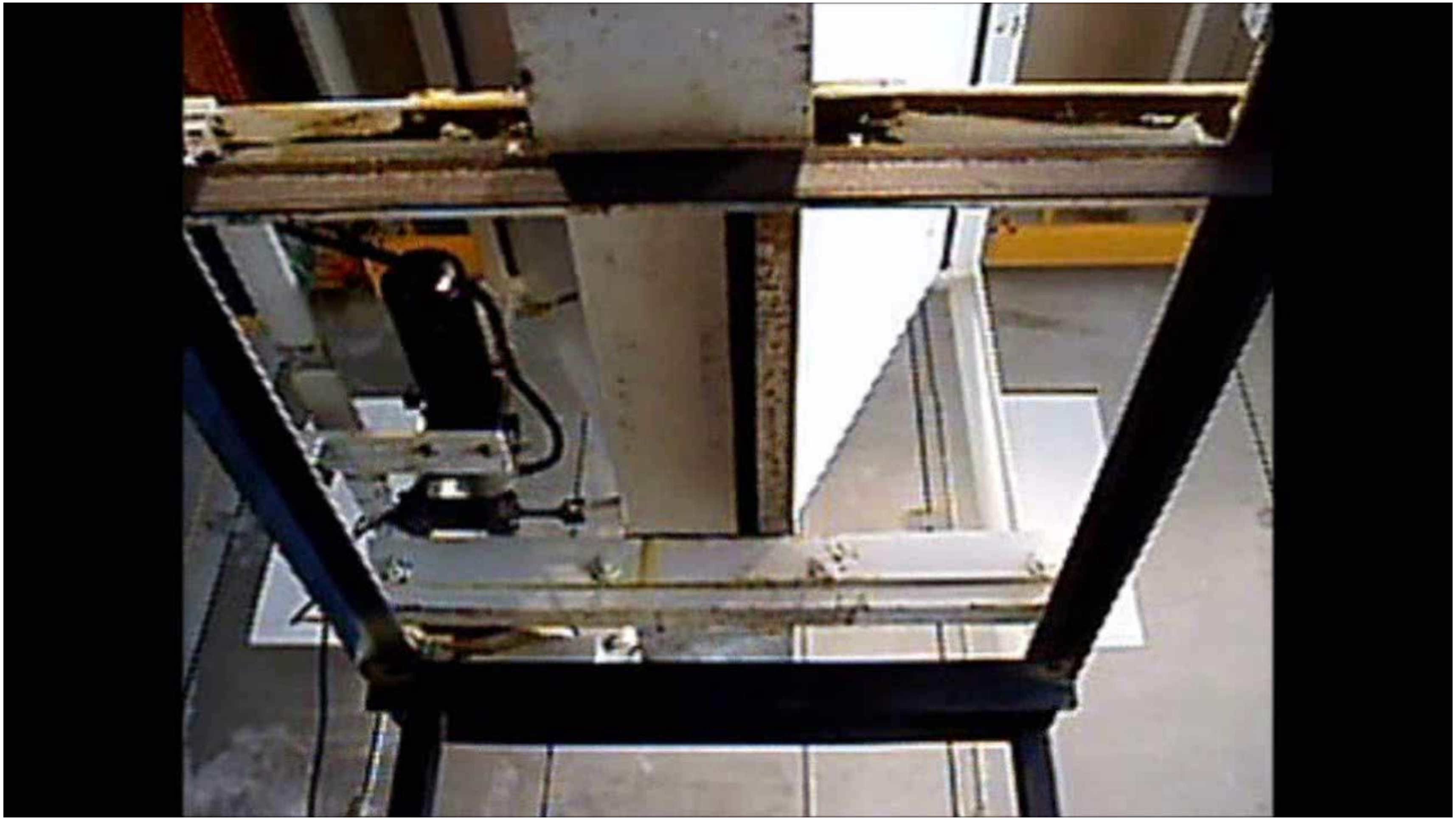


Particle Receiver Configurations

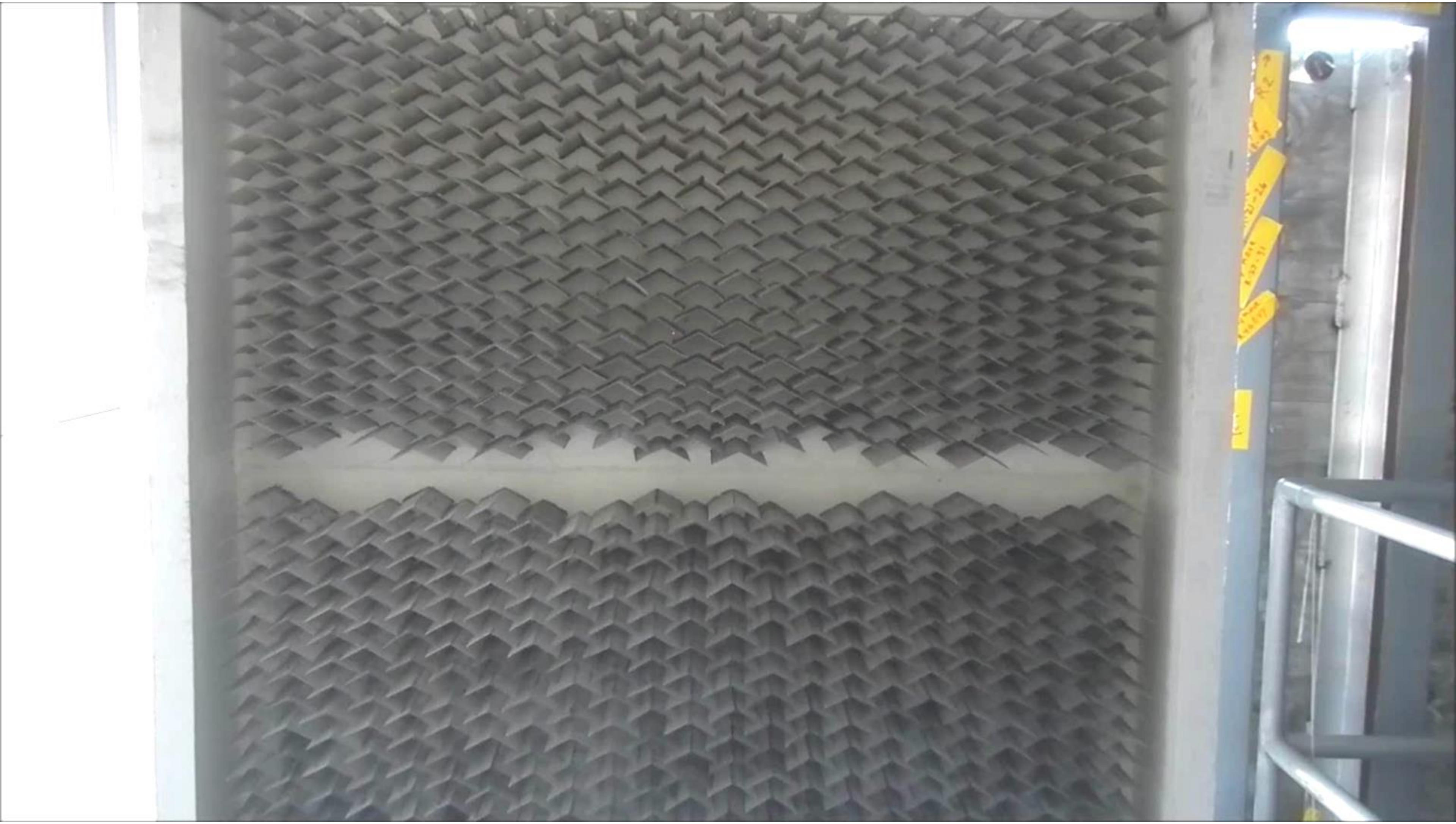


Cavity walls made from RSLE-57 (silica) insulating board; withstands temperatures up to 1200 C

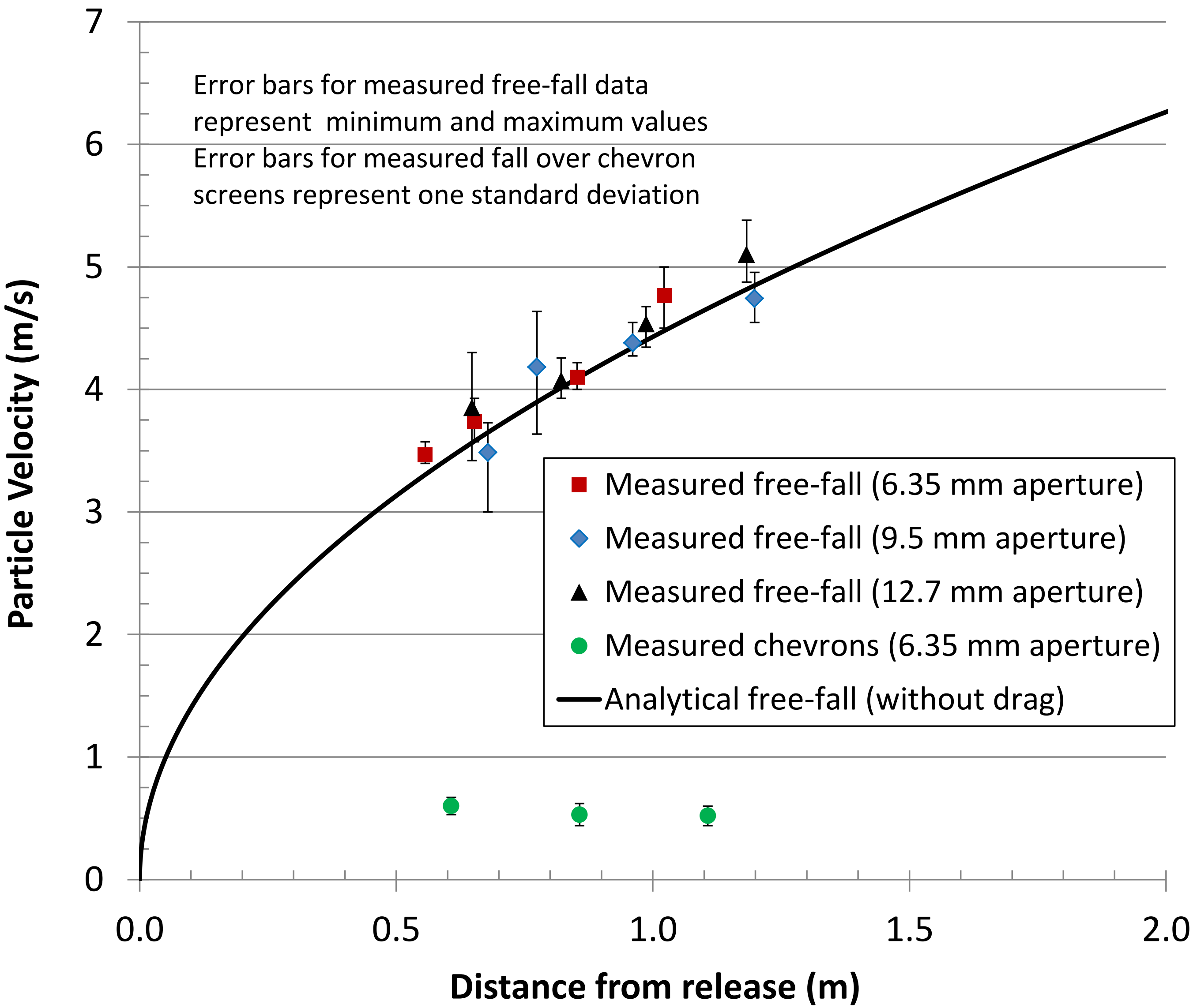
Free-Falling Design



Obstructed Flow Design

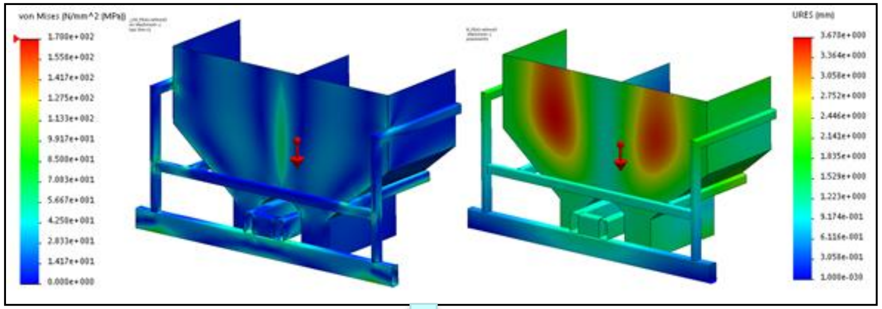


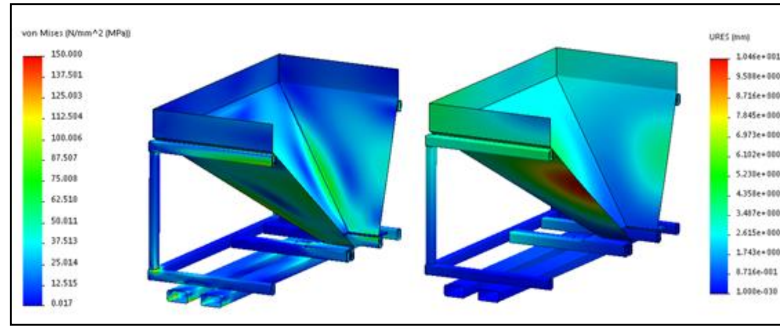
Particle Velocities



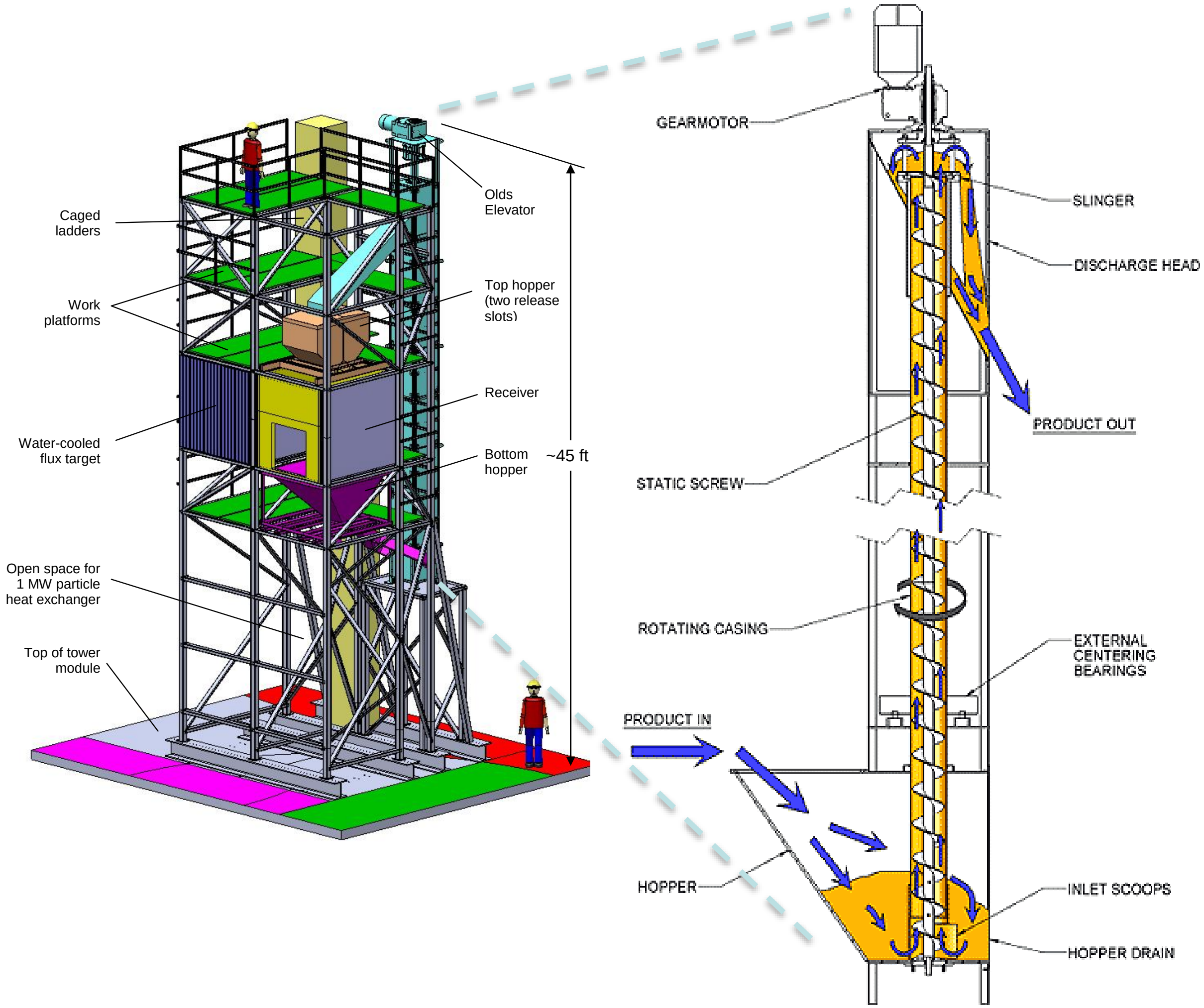
Ho, C.K., J. Christian, D. Romano, J. Yellowhair, and N. Siegel, 2015, *Characterization of Particle Flow in a Free-Falling Solar Particle Receiver*, in *Proceedings of the ASME 2015 Power and Energy Conversion Conference*, San Diego, CA, June 28 - July 2, 2015.

Top and Bottom Hoppers

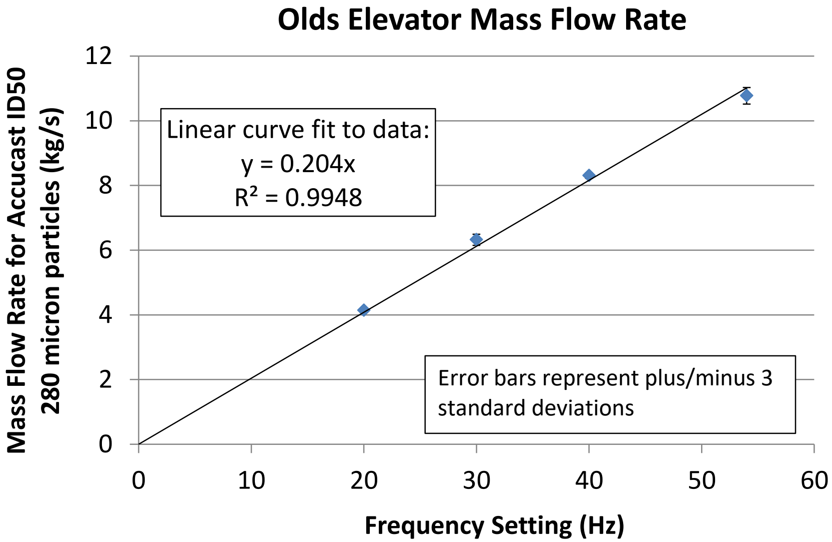




Olds Particle Elevator

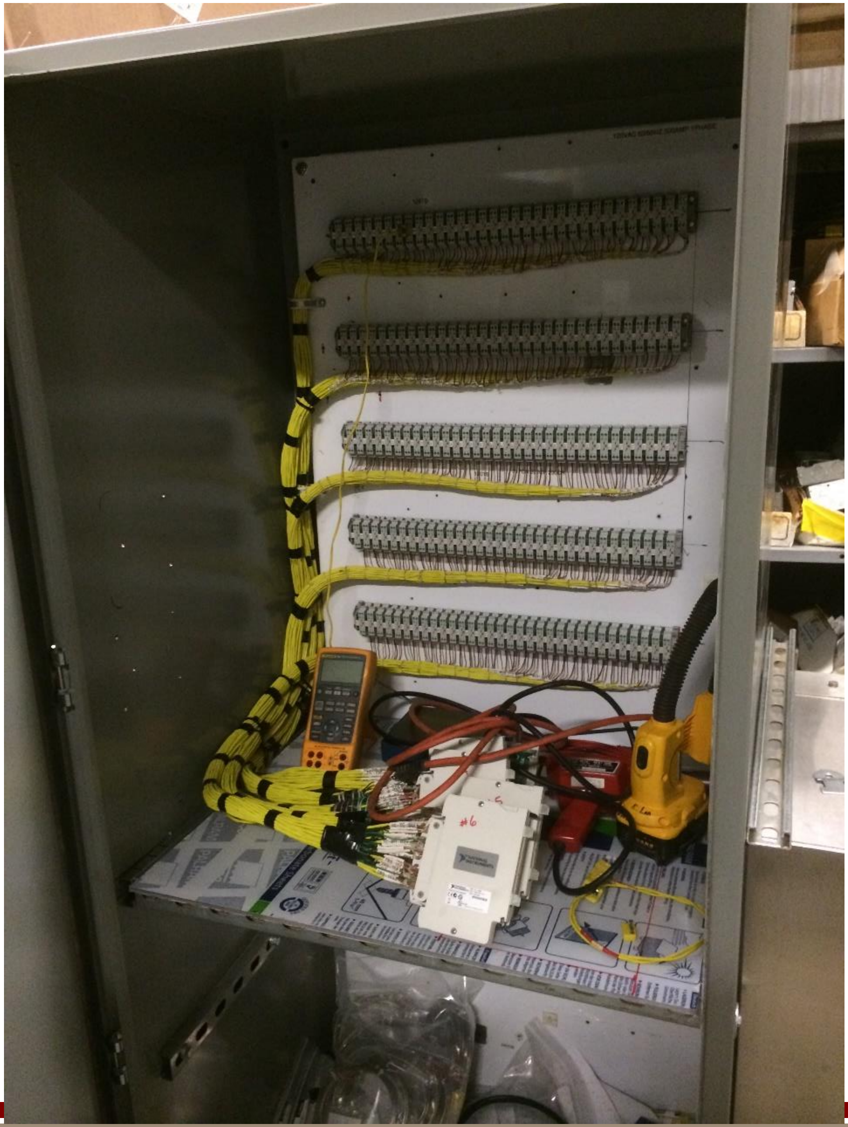


Olds Particle Elevator



Instrumentation and Data Acquisition

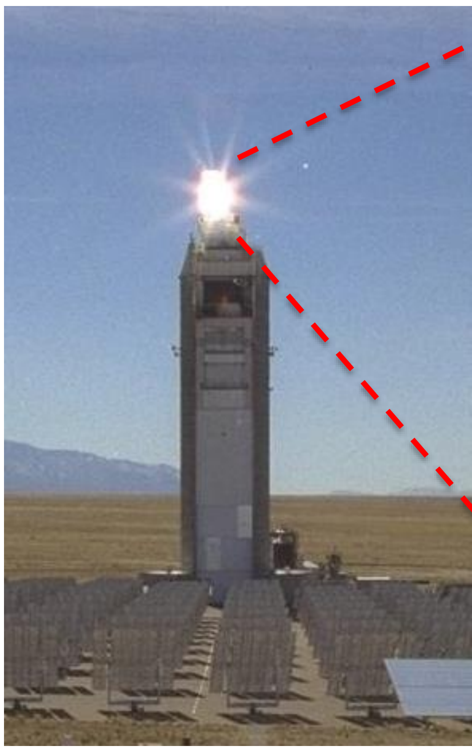
- 150 thermocouples, 6 flux gages
- Water cooling lines for radiometer and flux gauges
- DAQ cabinet for all modules/connections
- Power supply

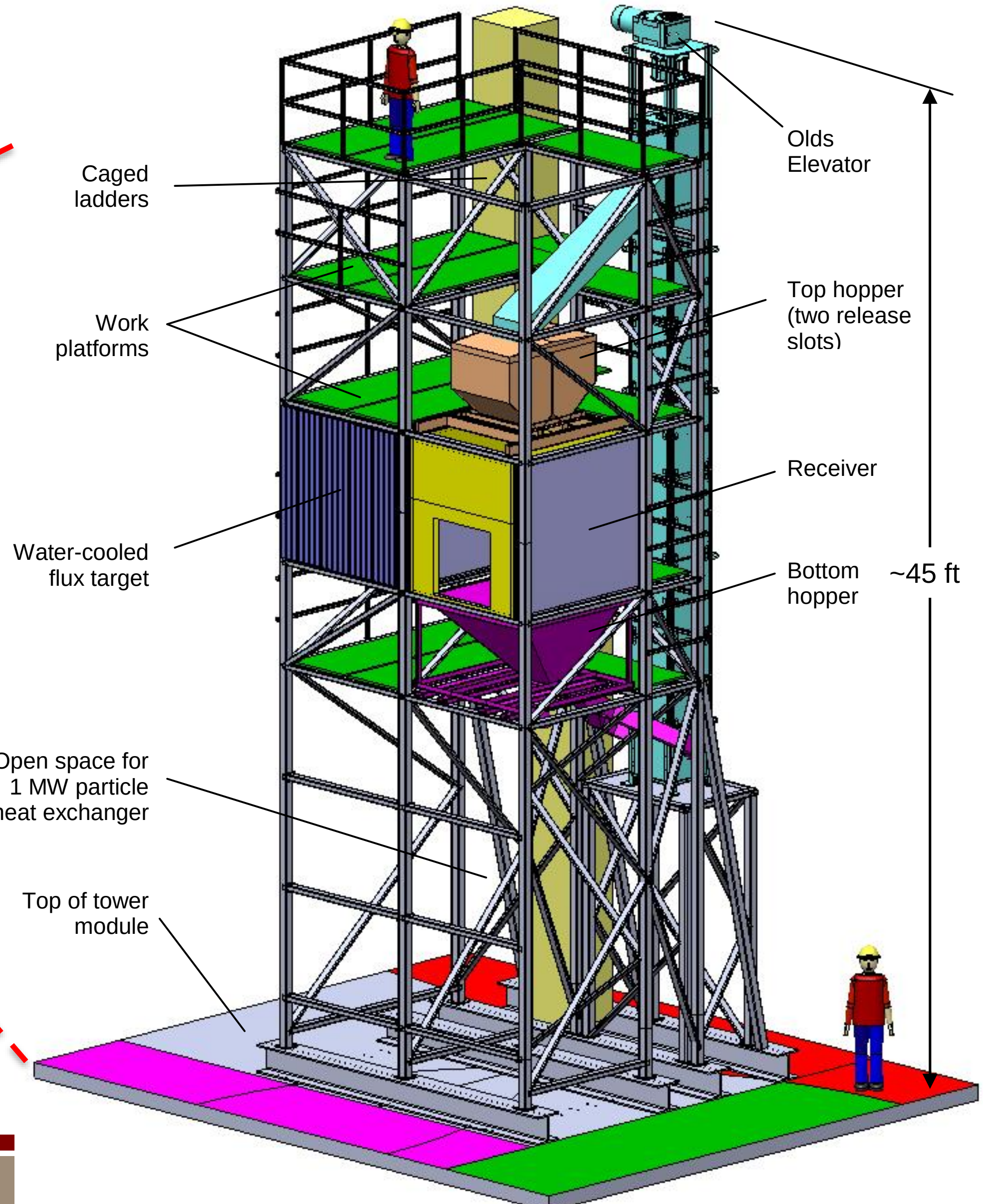


Phase 3

Final Assembly and On-Sun Testing

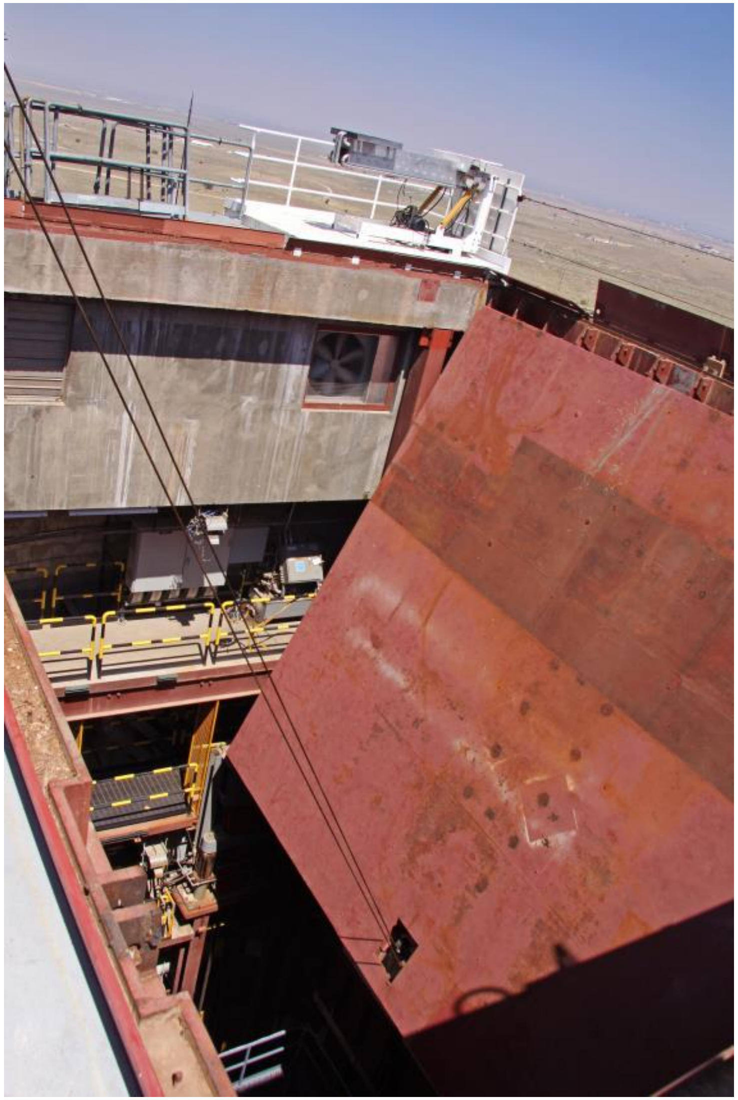
On-Sun Prototype System





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

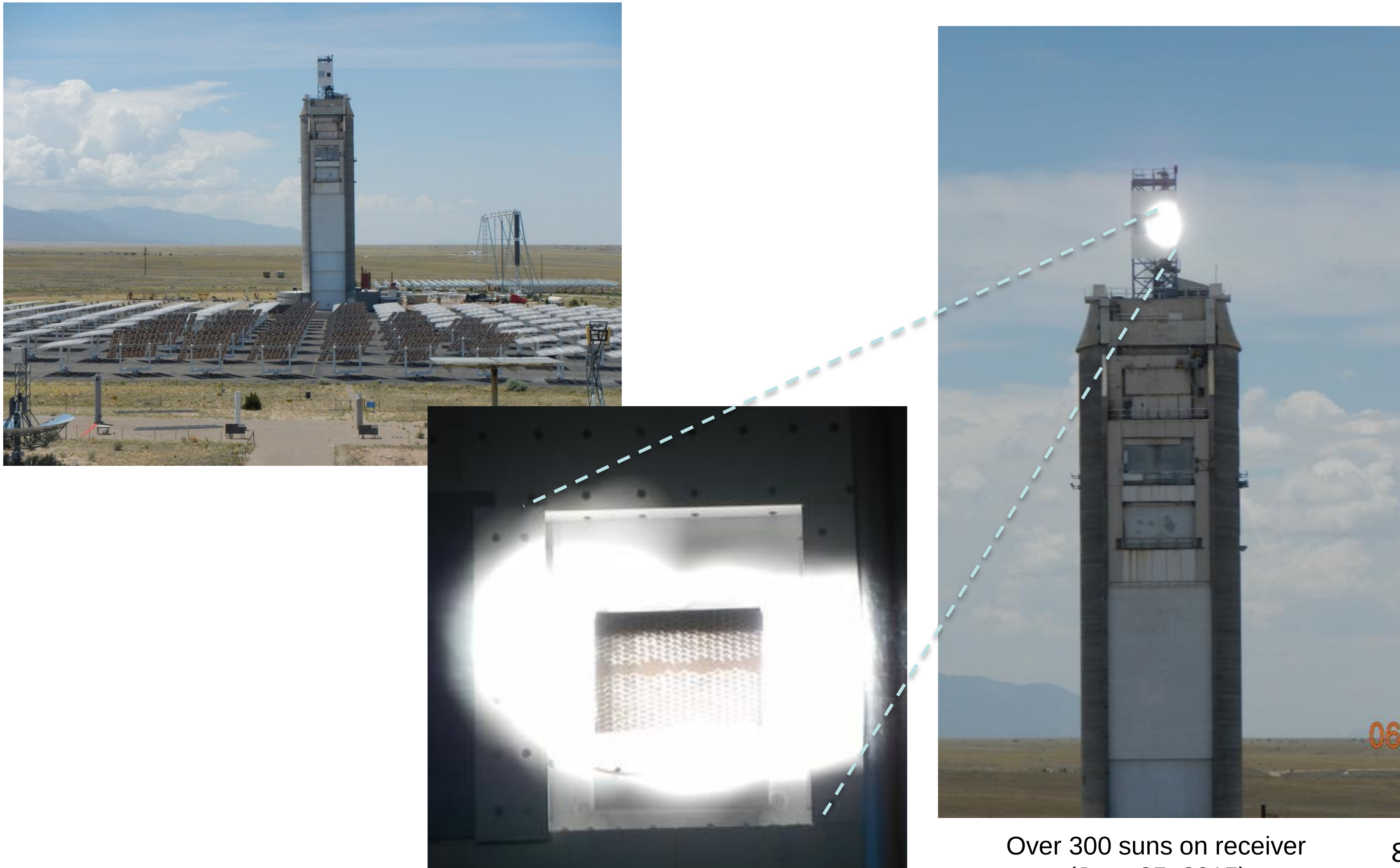
Lifting the system to the top of the tower



Lifting the system to the top of the tower

Receiver System on Top of Tower

On-Sun Tower Testing

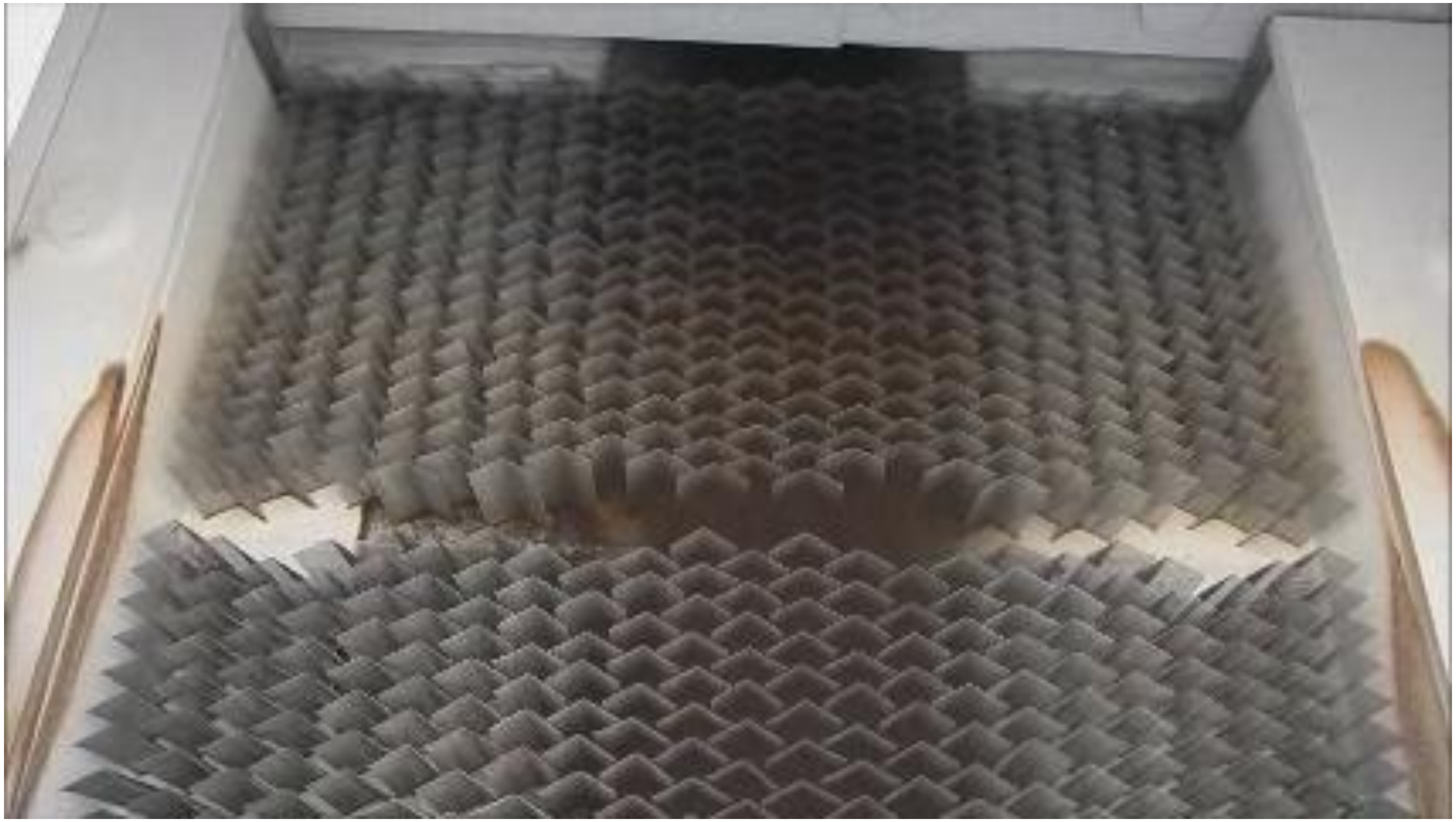


Over 300 suns on receiver
(June 25, 2015)

On-Sun Tower Testing

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

On-Sun Tower Testing

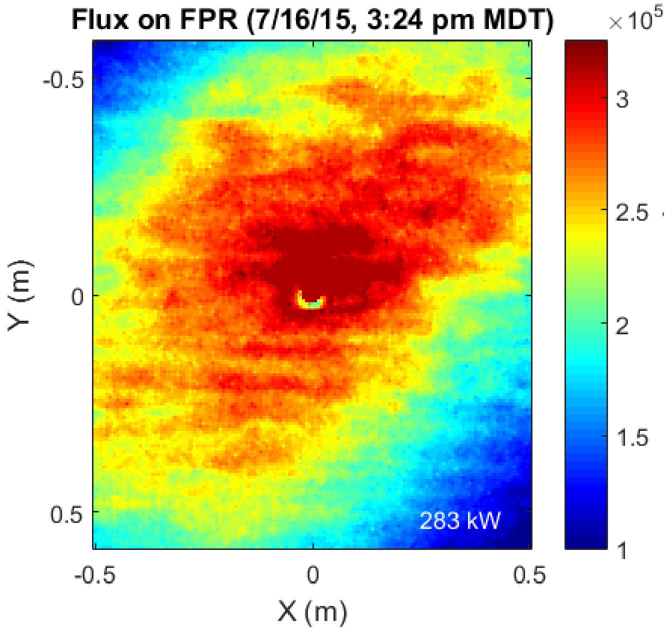


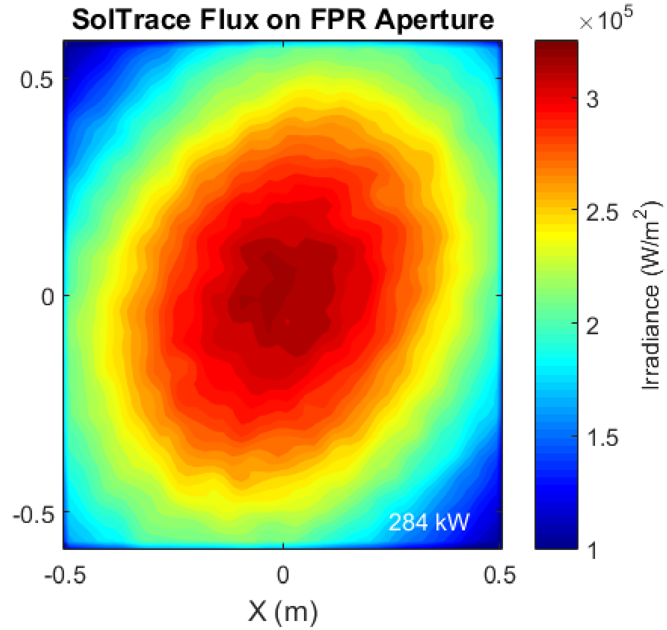
Particle Flow Through Mesh Structures
(June 25, 2015)

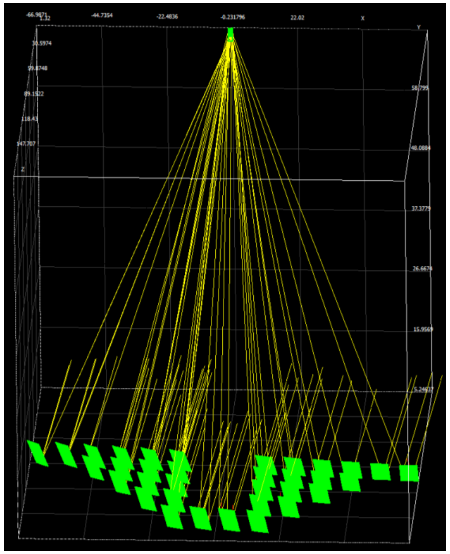
Test Protocol

- Select discharge slot aperture (1/4”, 3/8”, 7/16”)
  - Mesh insert could only accommodate ¼” slot (~3 kg/s/m)
- Heat falling particles with heliostat field
- At prescribed temperatures (~300, 500 C)
  - Apply prescribed fluxes (~500 and 1000 suns peak) to measure ΔT and thermal efficiency
  - Characterize irradiance distribution on flux target
  - Measure discharge time from top hopper to estimate mass flow rate
- Continue heating until average particle outlet temperatures exceeded 700 C

Irradiance Measurements



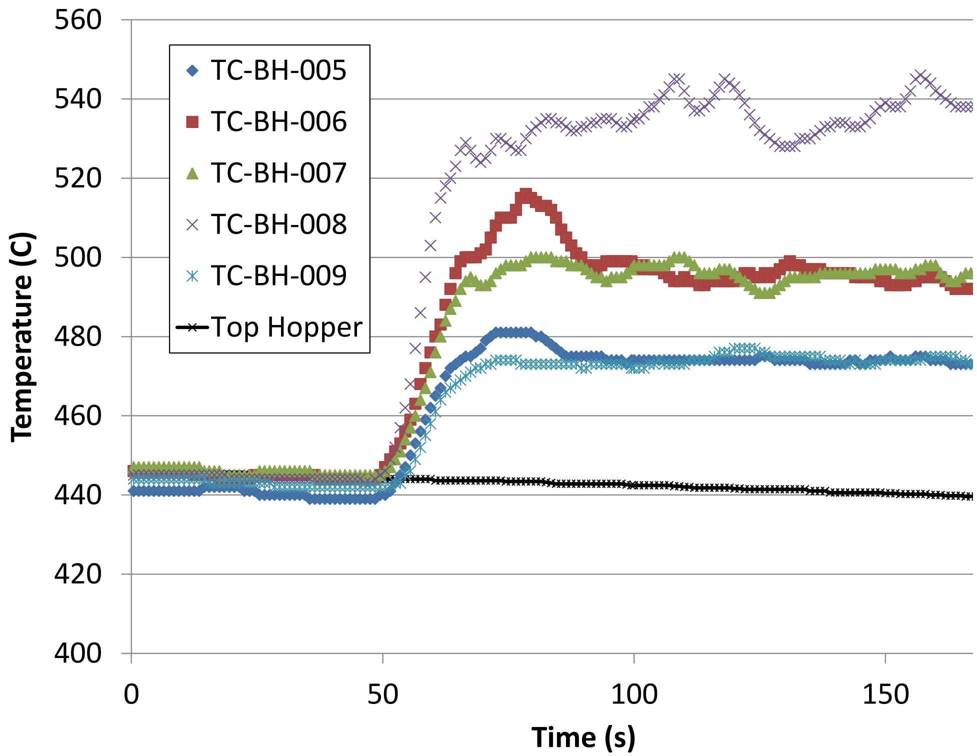


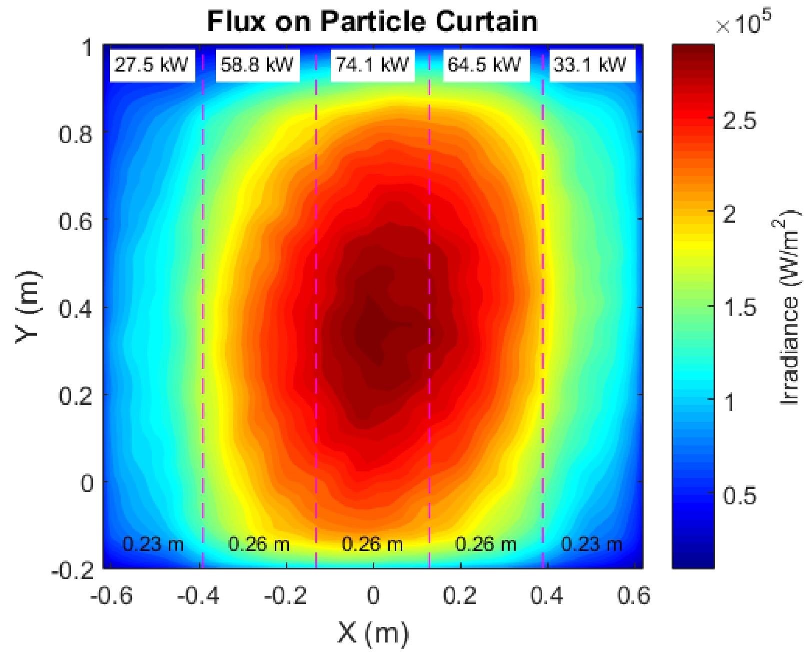


Measured

Simulated using Ray Tracing (SolTrace)

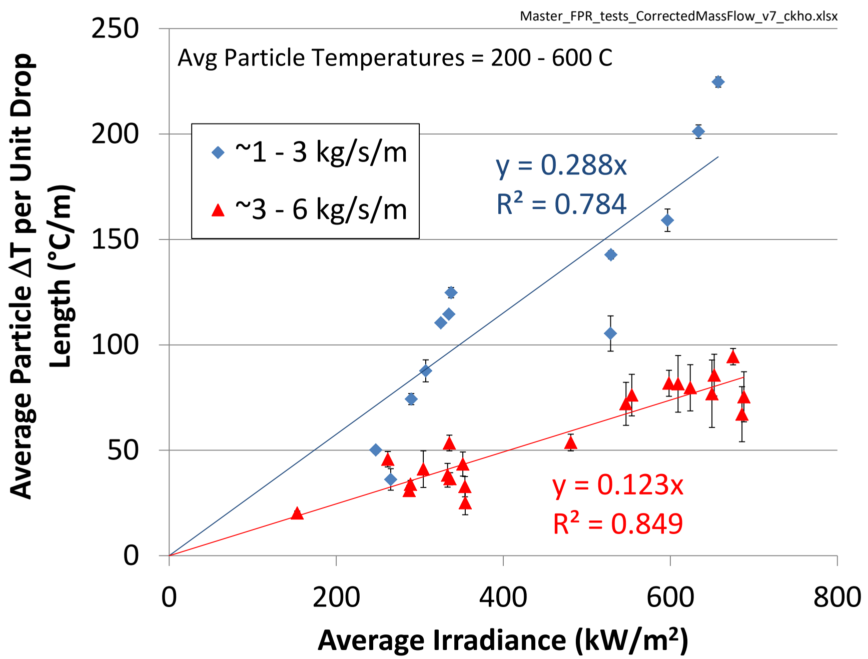
Temperature Measurements



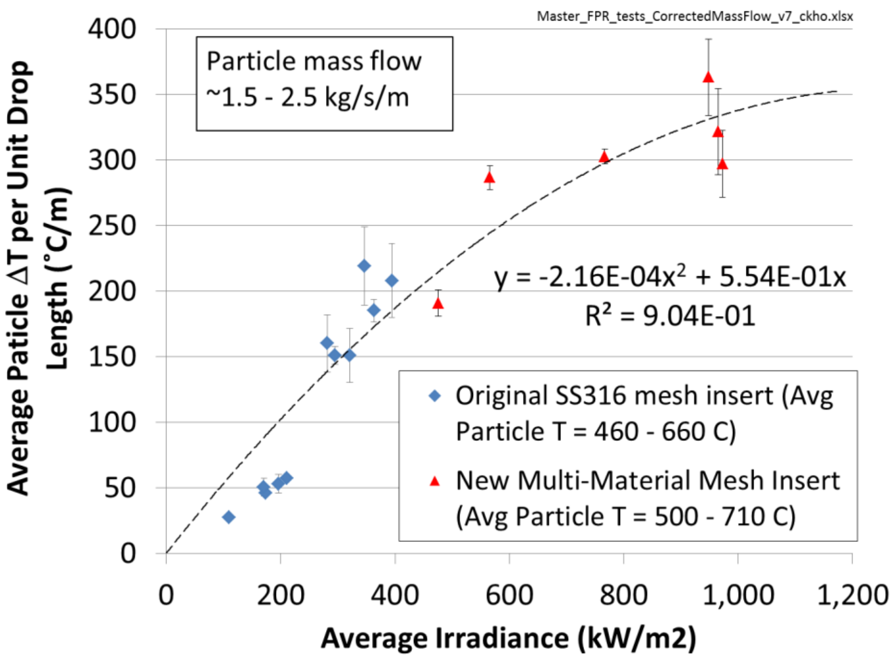


Particle Temperature Rise

Free Fall

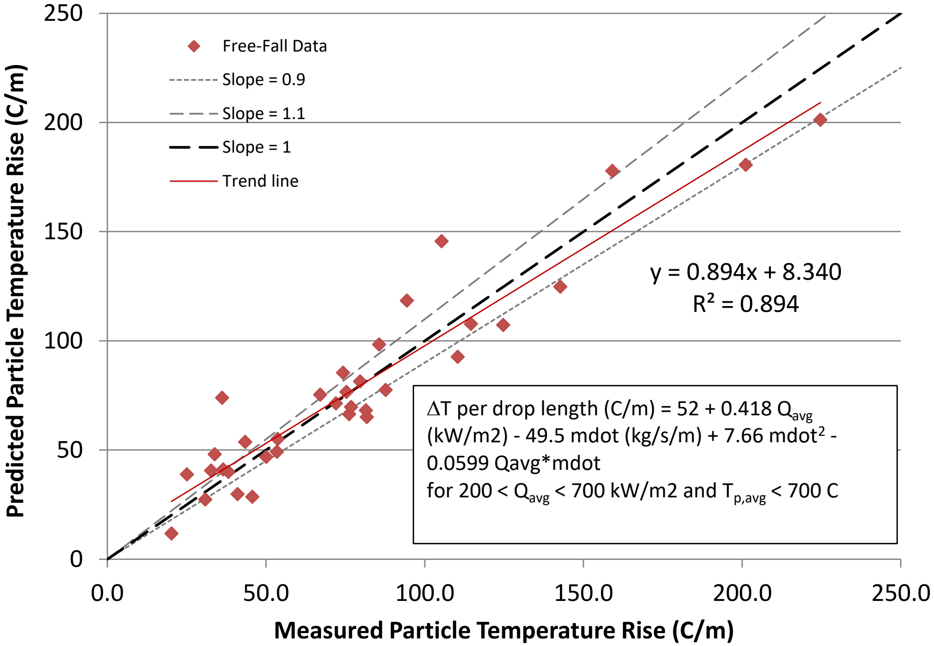


Obstructed Flow



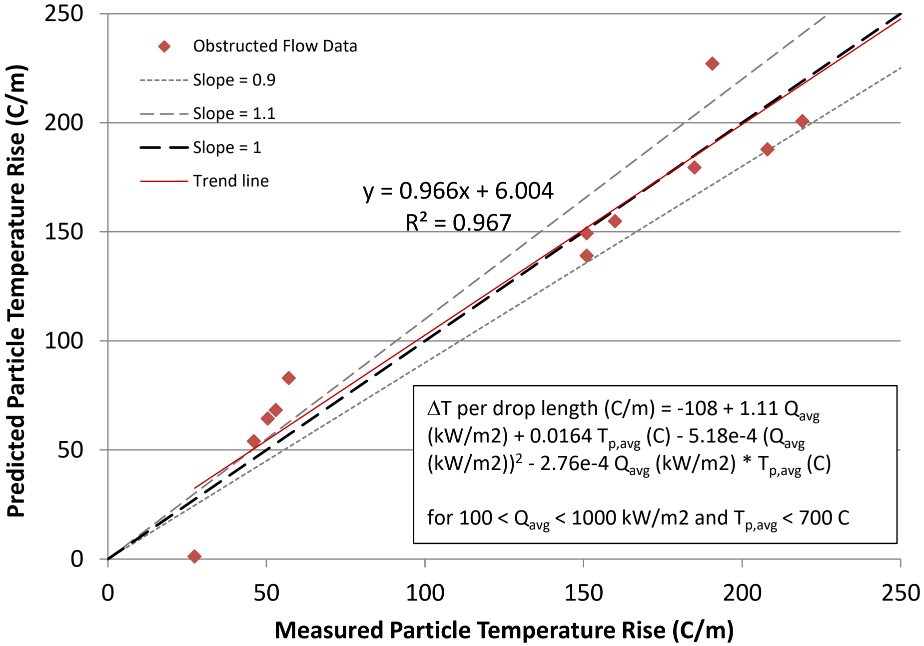
Particle Temperature Rise - Regressions

Free Fall



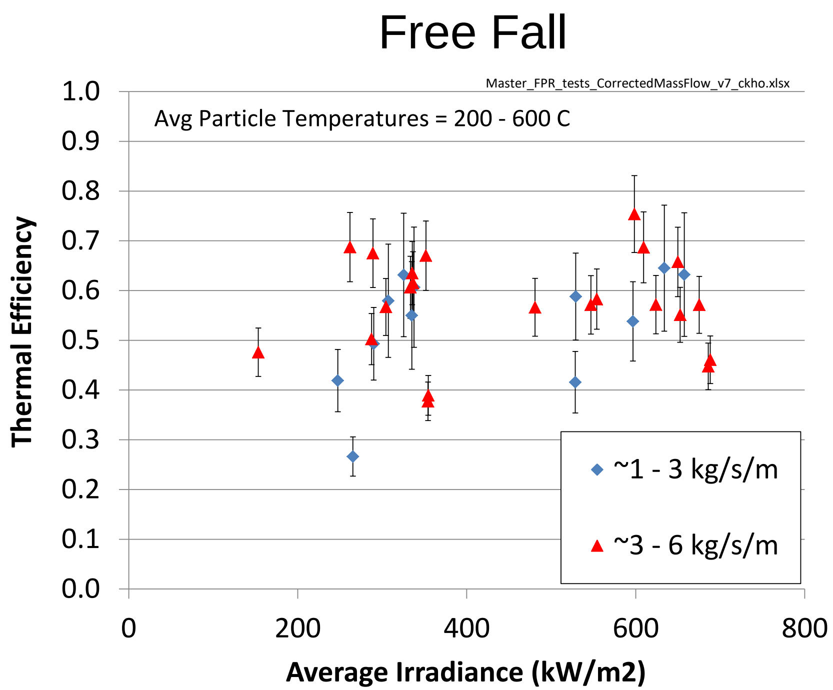
mdot ~ 1 – 6 kg/s/m

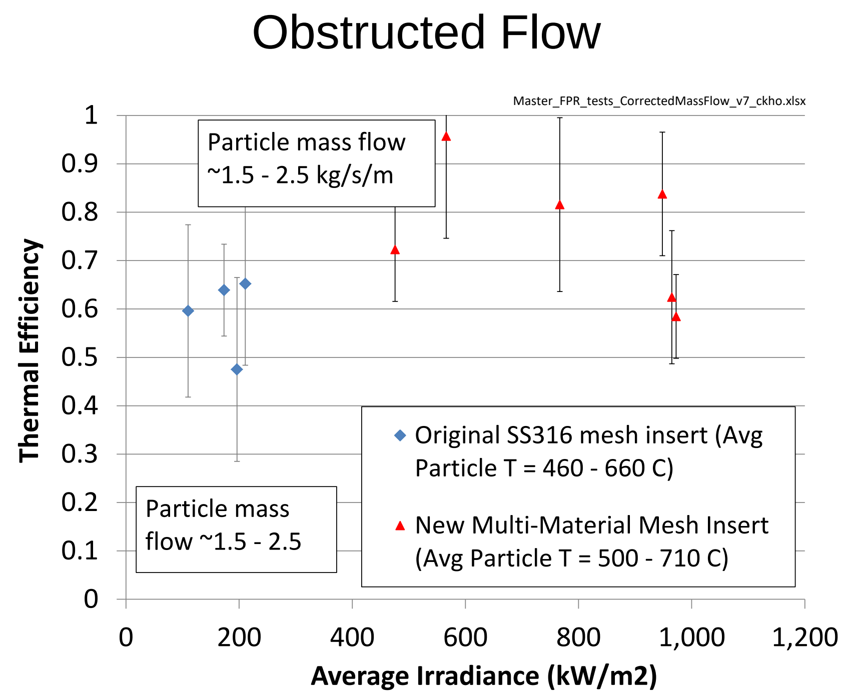
Obstructed Flow



mdot ~ 1.5 – 2.5 kg/s/m

Thermal Efficiency



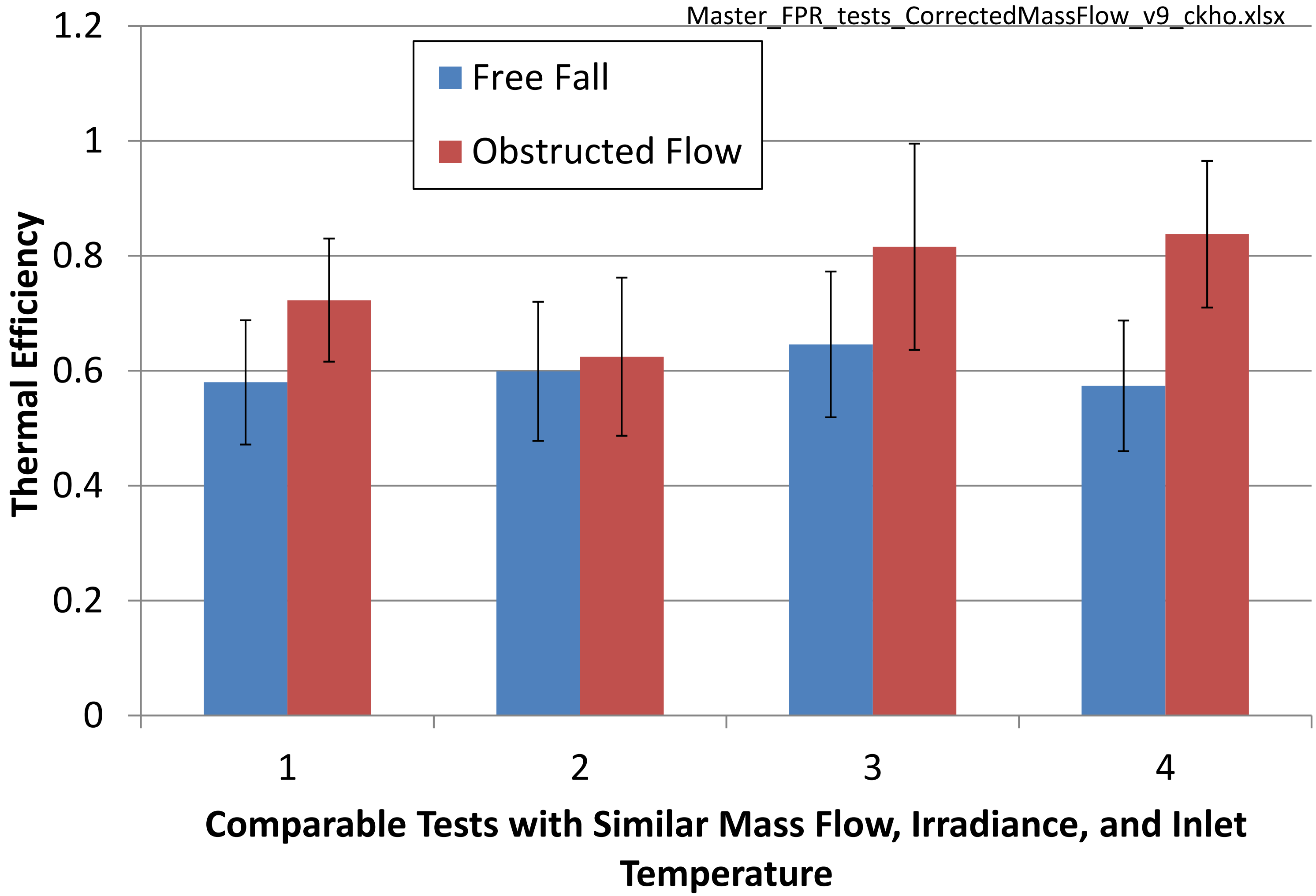


$$\eta_{th} = \frac{Q_{abs}}{Q_{in}} = \frac{\dot{m}\left(h_{out} - h_{in}\right)}{Q_{in}} = \frac{\dot{m}\int_{T_{in}}^{T_{out}} c_p\left(T\right)dT}{Q_{in}} = \frac{\dot{m}\left[\frac{365}{1.18}\left(T_{out}^{1.18} - T_{in}^{1.18}\right)\right]}{Q_{in}}$$

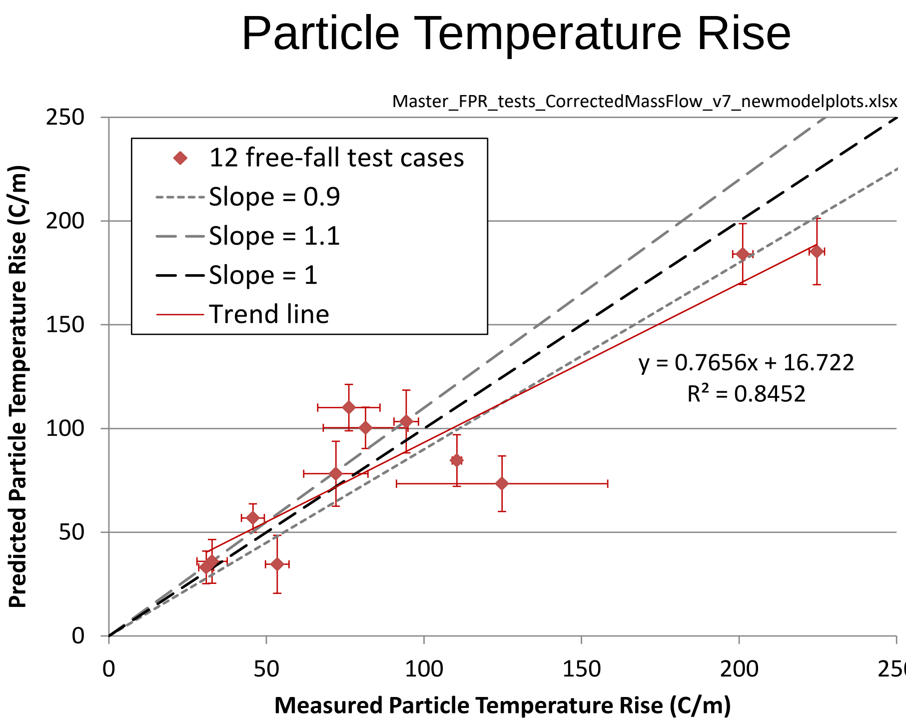
Summary of Recent Test Results with $T_{out} \geq 700$ C

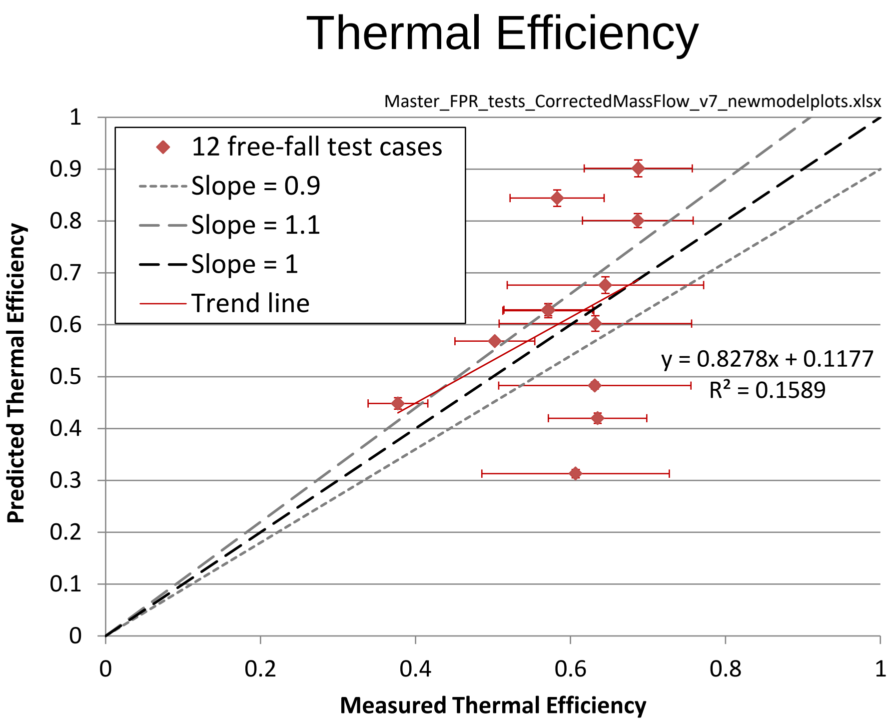
Date	Drop Type	Slot Aperture Thickness (in)	Average Irradiance (kW/m^2)	Mass Flow Rate (kg/s/m)	Bulk Temperature Out (Celsius)	Delta T (Celsius)	Particle Curtain Thermal Efficiency	Plus/Minus Efficiency	Plus/Minus Delta T
2/25/2016	Free Fall	0.44	354.17	3.45	701.86	32.76	0.38	0.04	4.82
2/25/2016	Free Fall	0.44	546.92	3.70	696.85	72.06	0.57	0.06	10.20
4/3/2016	Obstructed Flow	0.25	972.50	1.66	842.25	297.16	0.58	0.09	25.46
4/4/2016	Obstructed Flow	0.25	964.98	1.60	902.10	321.41	0.62	0.14	32.93
2/26/2016	Free Fall	0.25	657.42	1.62	707.47	224.68	0.63	0.12	2.45
3/10/2016	Free Fall	0.38	335.50	3.38	703.73	53.45	0.64	0.06	3.74
4/3/2016	Obstructed Flow	0.25	475.72	1.56	768.88	190.69	0.72	0.11	10.05
4/4/2016	Obstructed Flow	0.25	766.90	1.85	733.48	302.64	0.82	0.18	5.78
4/3/2016	Obstructed Flow	0.25	948.16	2.00	719.71	362.96	0.84	0.13	29.36

Free-Fall vs. Obstructed Flow

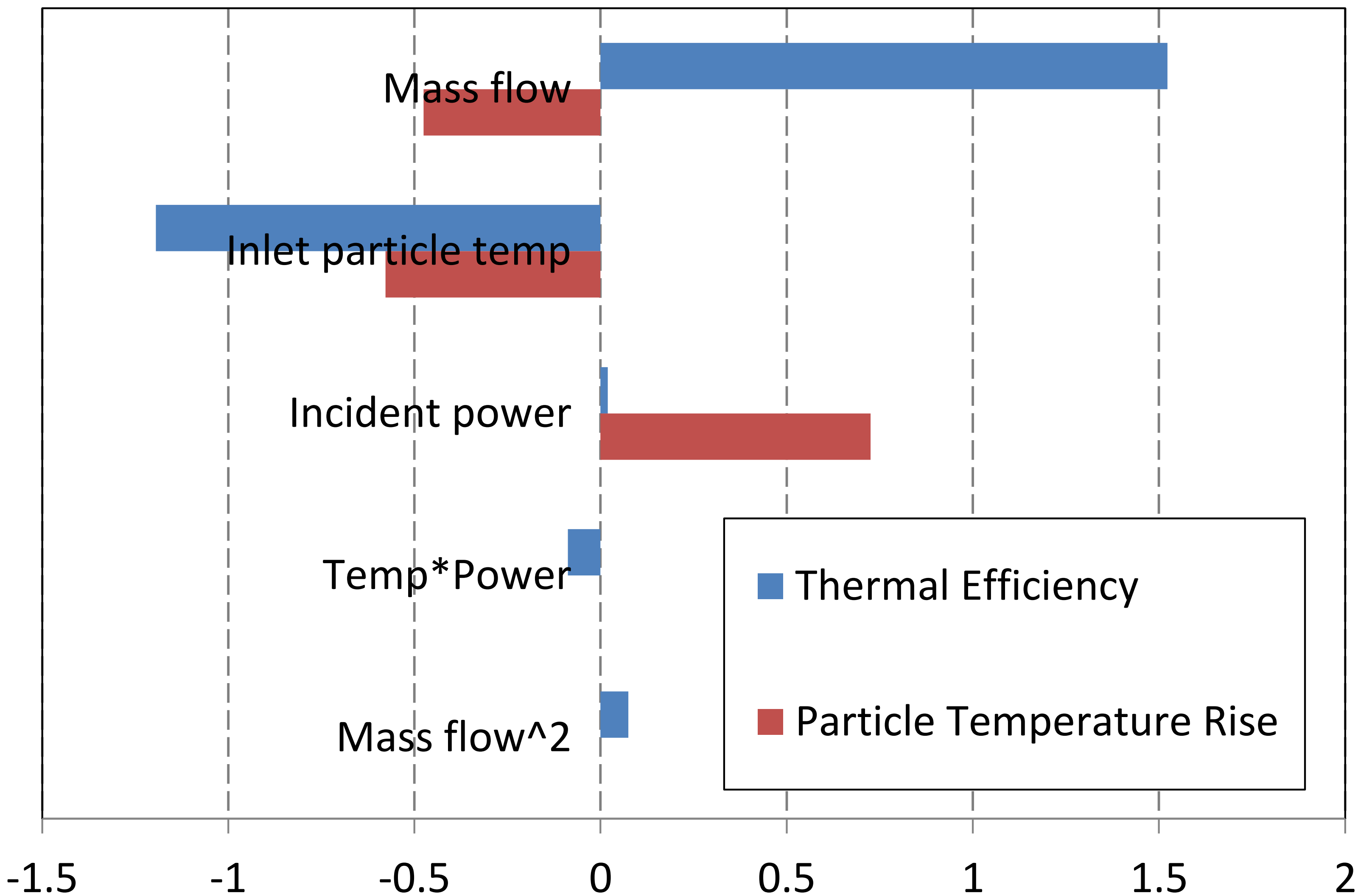


CFD Modeling of Free-Fall Tests

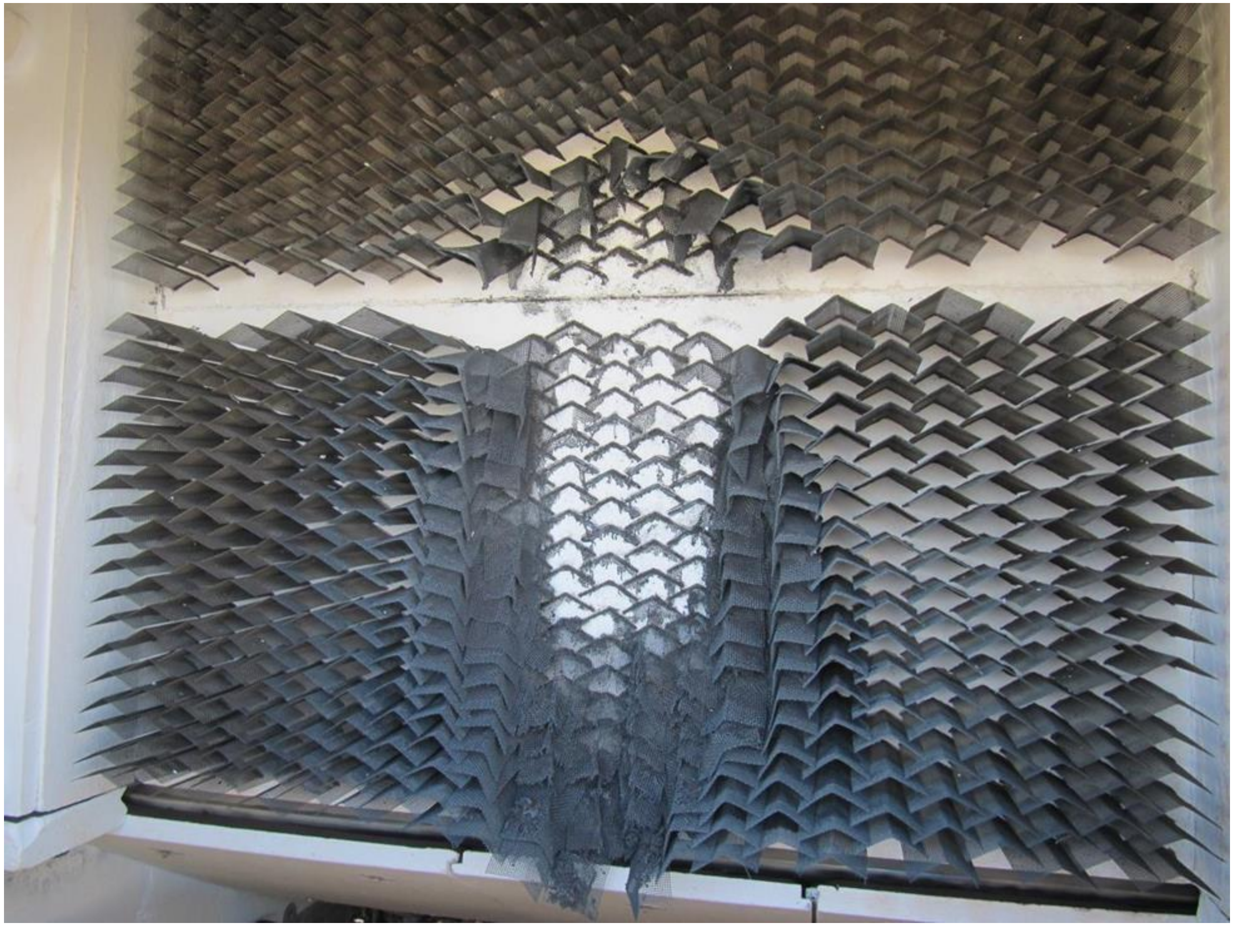




Modeling Rank Regression Coefficients

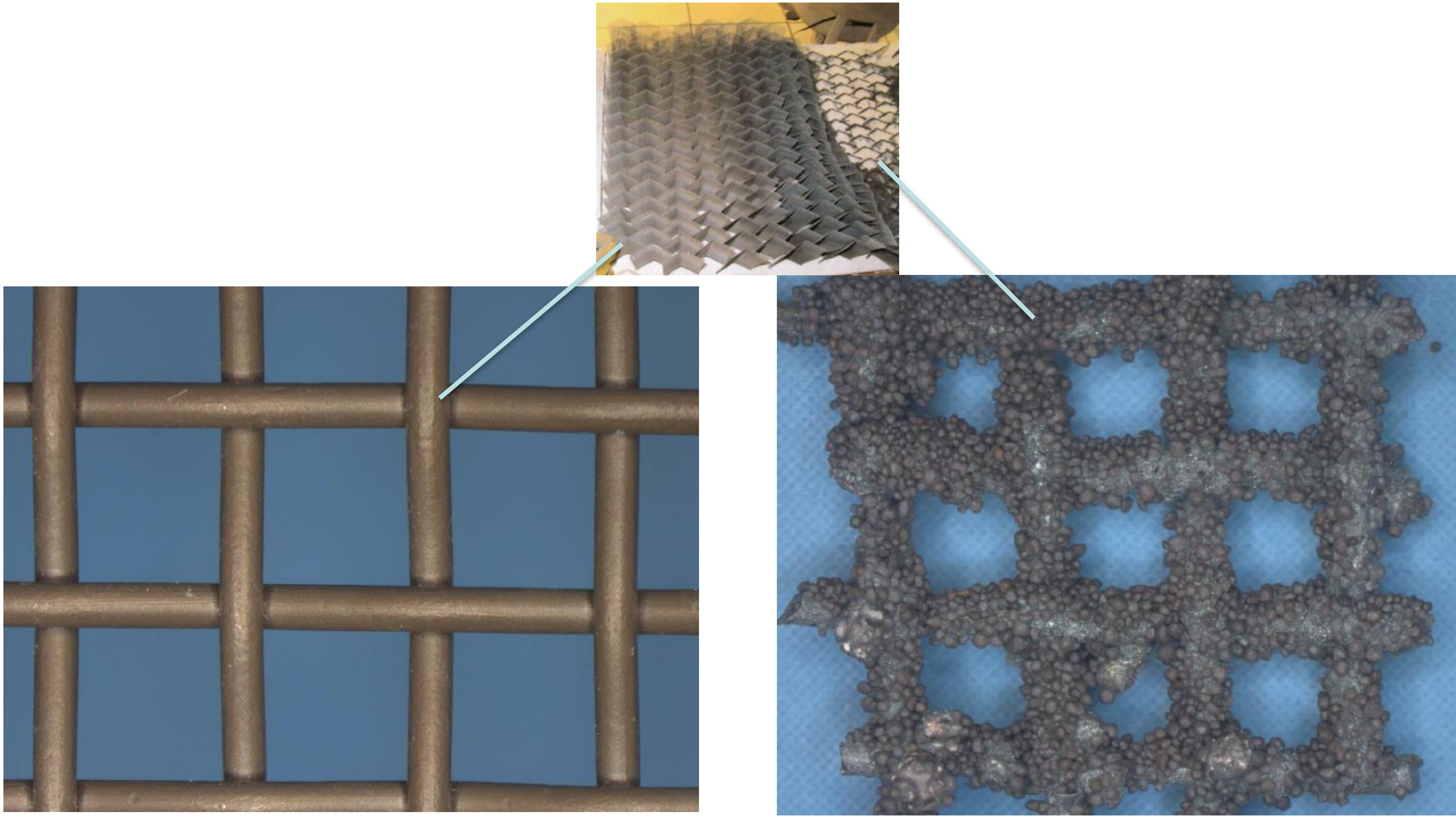


Mesh Structure Reliability



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

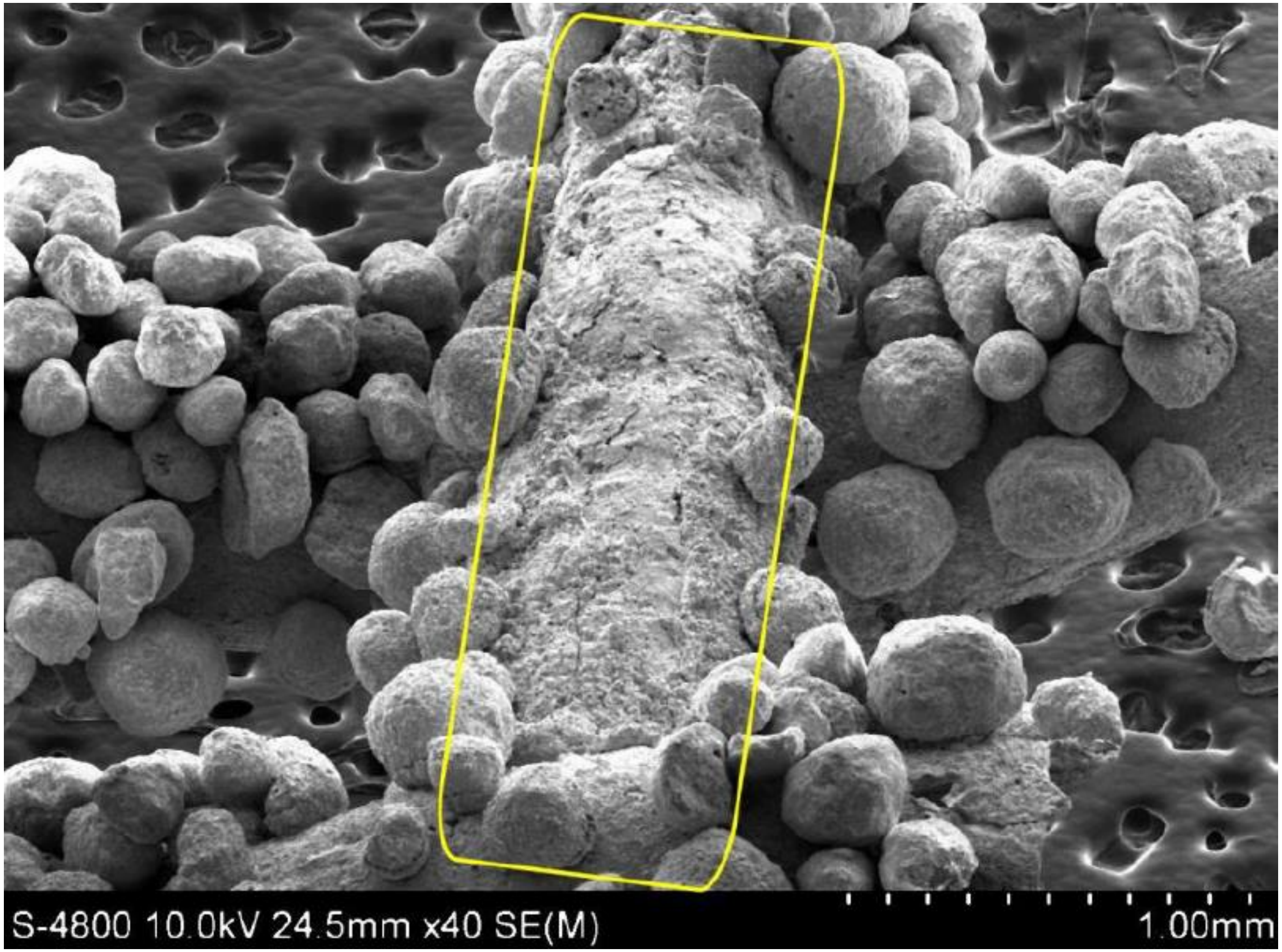
SS316 Mesh Failure Analysis



Mesh located far from failed region

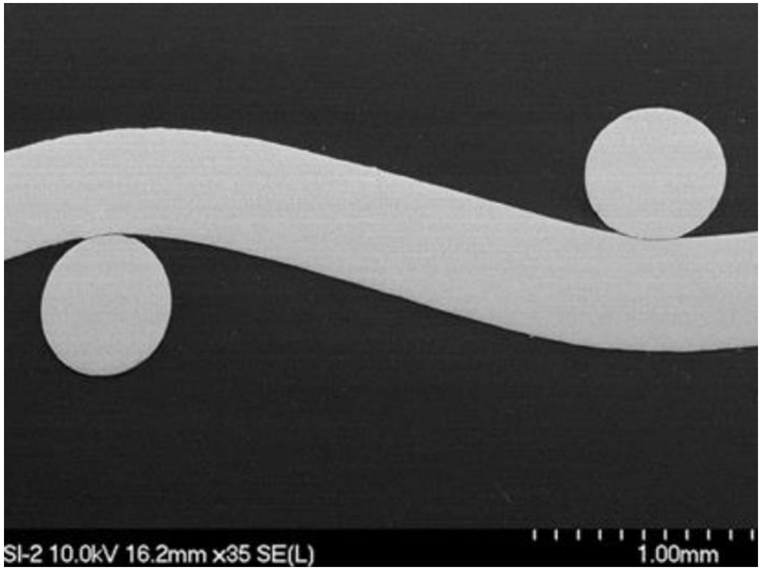
Mesh located within failed region
(ceramic particles sintered on mesh)

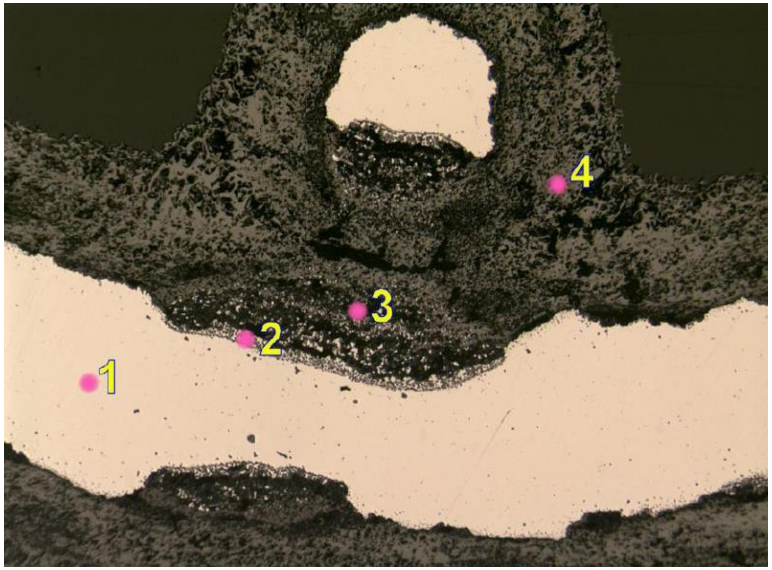
SS316 Mesh Failure Analysis



SEM of oxidized mesh

SS316 Mesh Failure Analysis



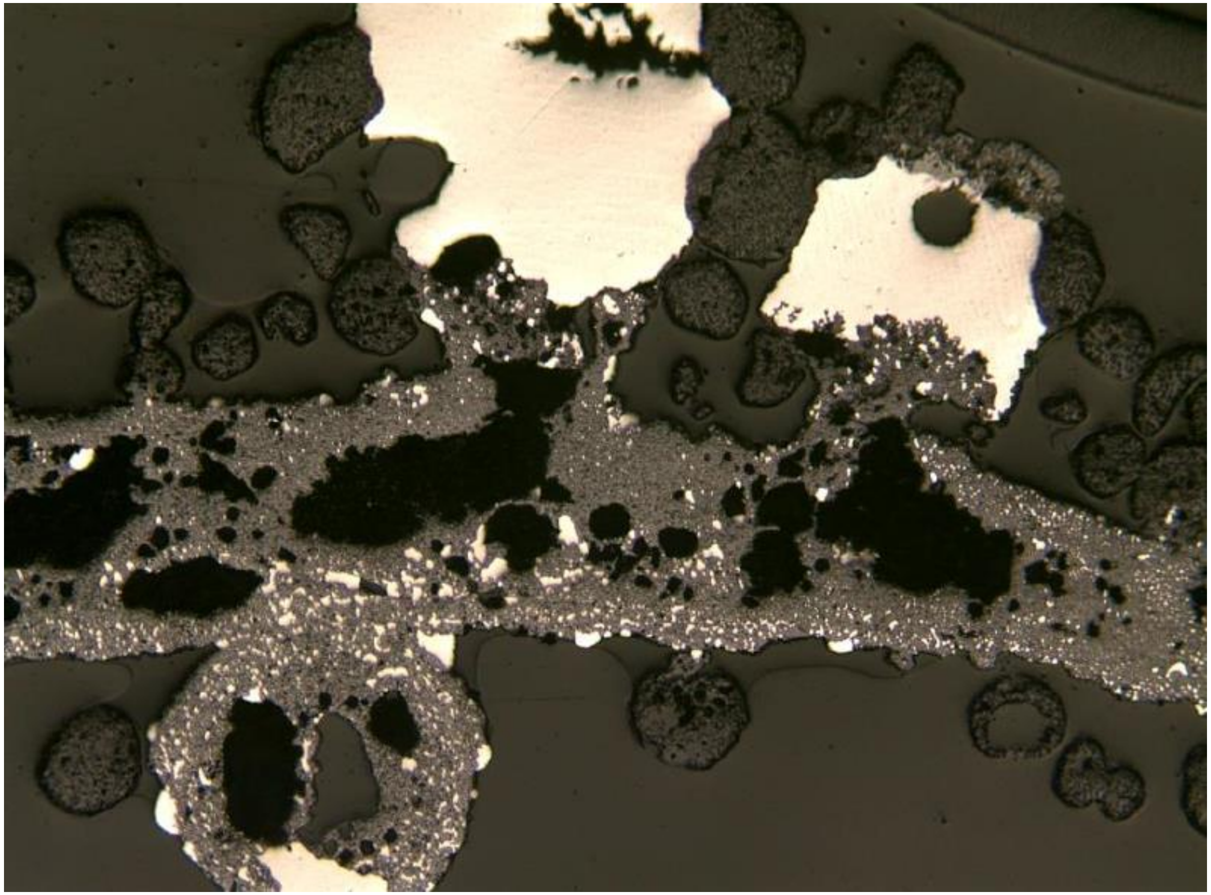


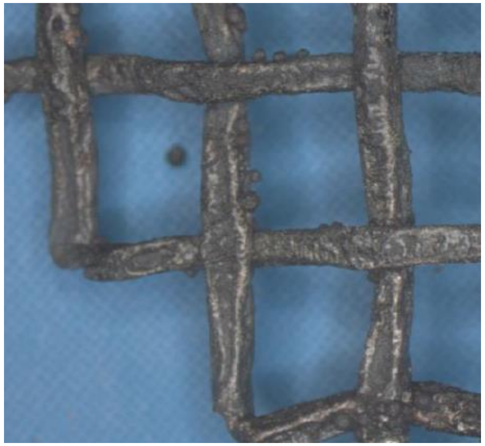
Top left: cross-sectional view of intact wire mesh

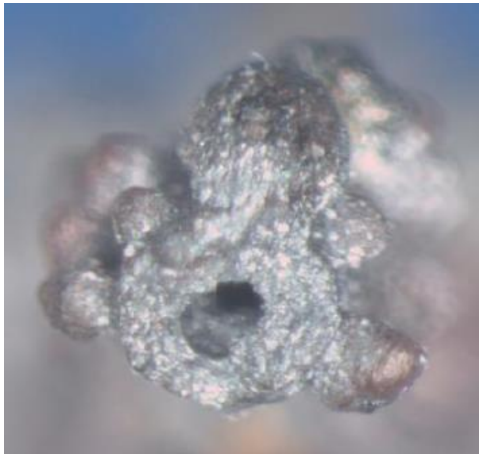
Top right: cross-sectional view of oxidized wire mesh

	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

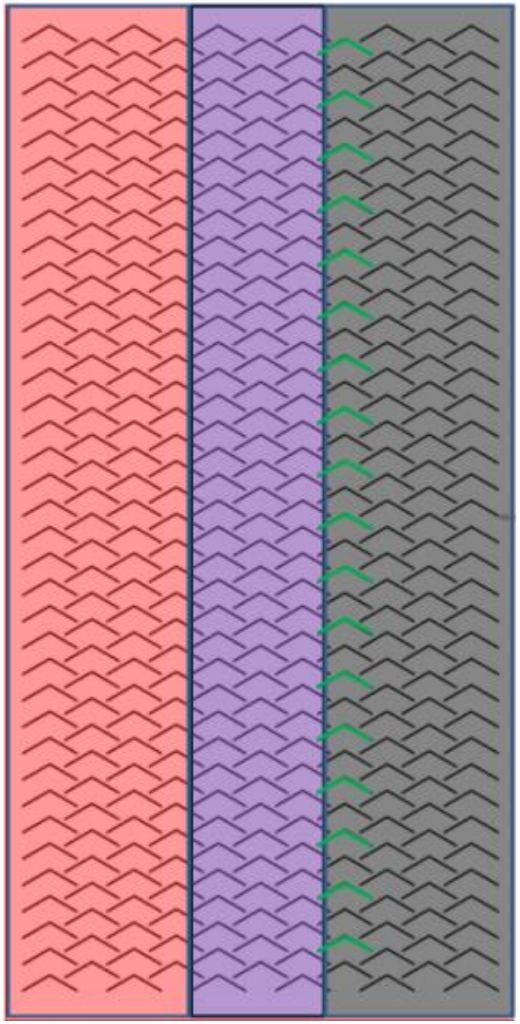






Cross-sectional view of oxidized wire mesh; wire ruptured and “leaked” molten steel out of oxidized shell (white is stainless steel, rough gray area is oxidized mesh)

Multi-Material Mesh Insert



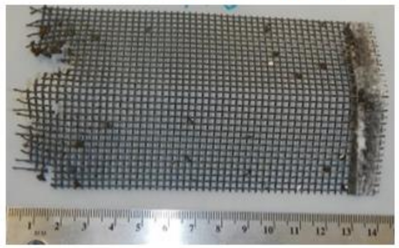
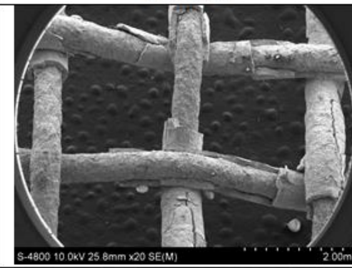
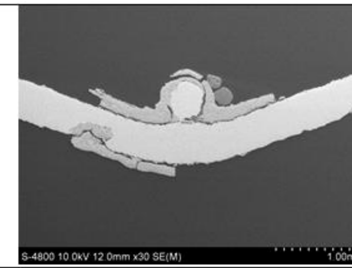
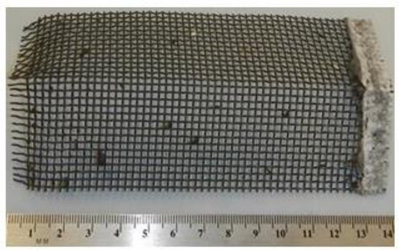
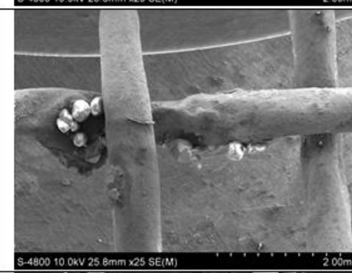
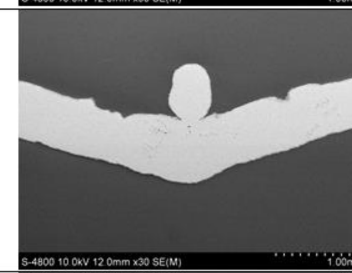
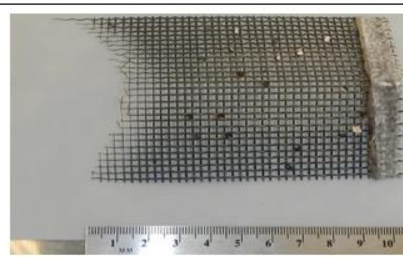
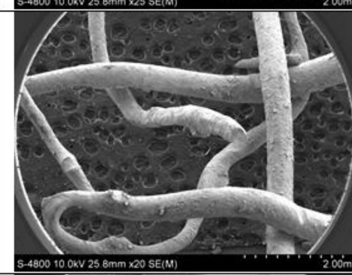
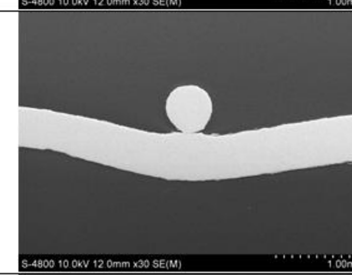
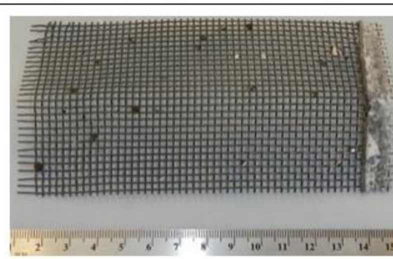
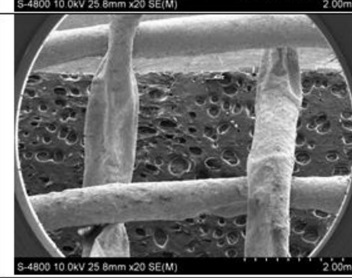
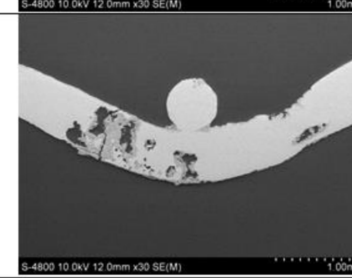
SS316

Inconel 601

Hastelloy C276

Hastelloy X

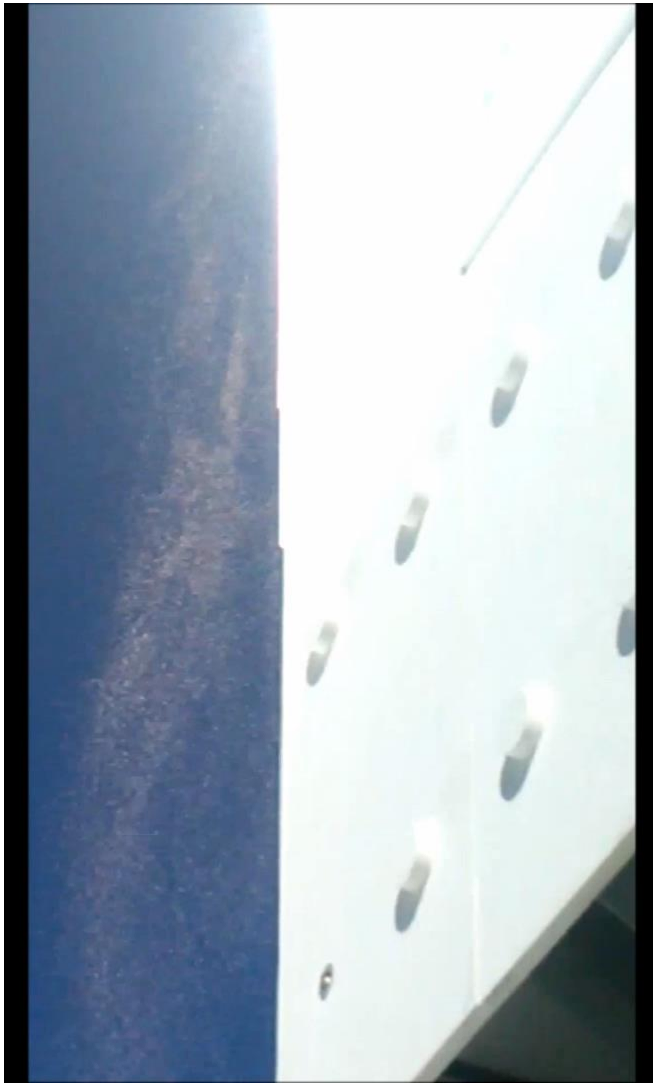
SEM Analysis of Multi-Mesh Materials

Material	Mesh Sample Pulled from Insert (left edge faced incident irradiation)	SEM Image of Damaged Interwoven Wires	SEM Cross Section
SS316			
Inconel 601			
Hastelloy C276			
Hastelloy X			

Particle Loss and Characterization

Particle Loss during On-Sun Tests

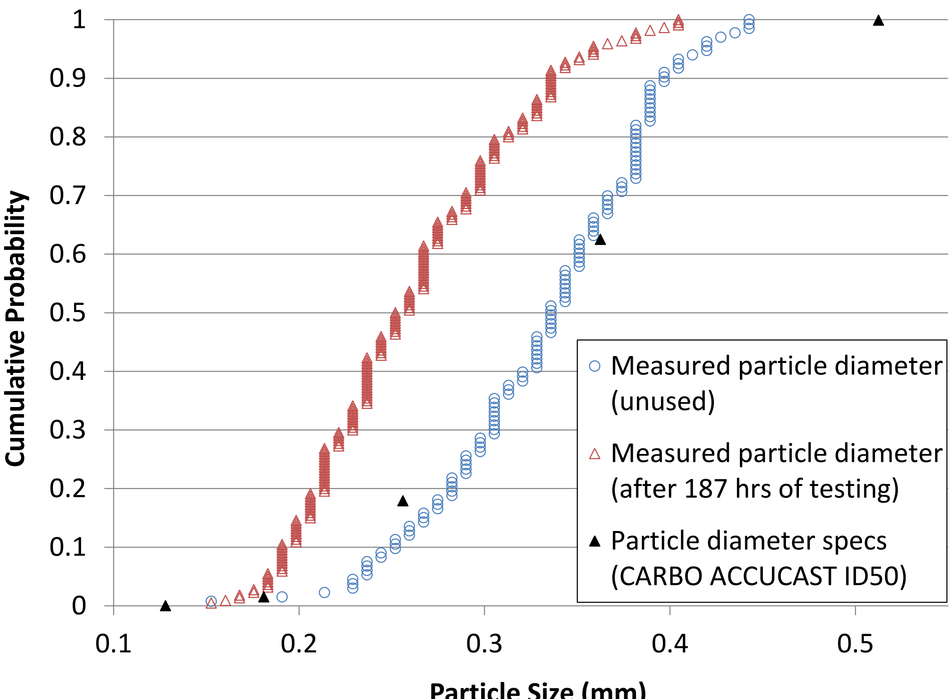
- Average particle loss during ~200 hours of testing was 0.06% of average particle mass flow, or ~9.4 kg/hr
  - ~60% due to loss through aperture (5.8 kg/hr)
  - ~40% due to attrition from wear (3.6 kg/hr)
- Significant particle loss during south wind
- Mitigation measures
  - Deeper cavity; particle release further from aperture
  - Aperture coverings
  - Wind diverters

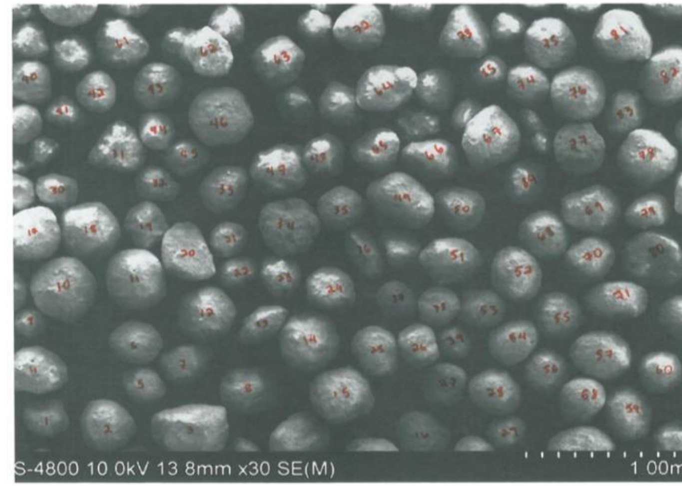


Nov. 2, 2015
3/8” slot – free fall
280 micron
ACCUCAST ID50
10-15 mph south wind
500 – 1000 suns

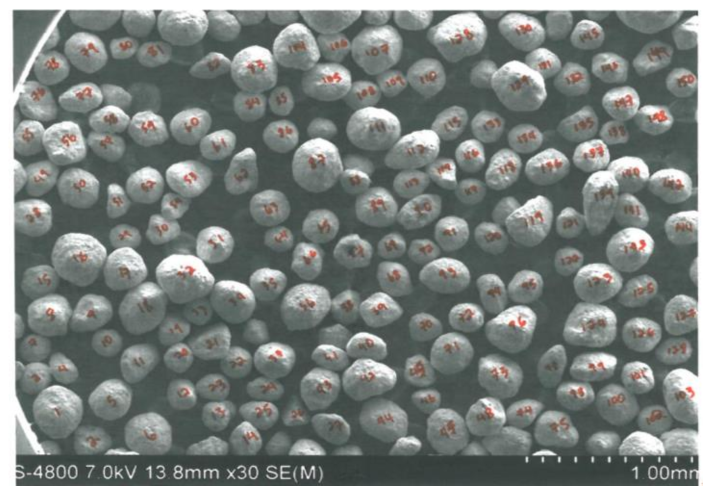
Particle Attrition

- Particle attrition due to friction and wear was ~0.02% of particle mass flow rate, or 3.6 kg/hr
  - High friction from Olds elevator





Unused particles



After 187 hours of testing in receiver prototype

Particle Solar Absorptance

- Particle packed-bed solar absorptance after nearly 200 hours of testing (0.946 ± 0.003) was similar to unused particles (0.945 ± 0.001)
  - Hematite formation on surface may be worn away

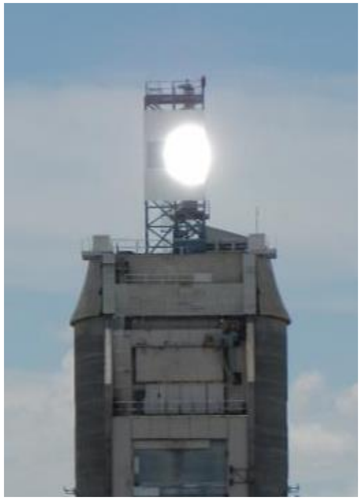
Element	Unused CARBO ACCUCAST ID50 (wt%)	Used CARBO ACCUCAST ID50 (after 187 hrs of testing) (wt%)
O	45 - 46	46 - 47
Al	38 - 39	37 - 38
Si	8.9 - 9.6	6.5 - 8.8
Ti	1.3 - 1.4	1.2 - 1.3
Fe	5.2 - 5.4	6.7 - 7.9

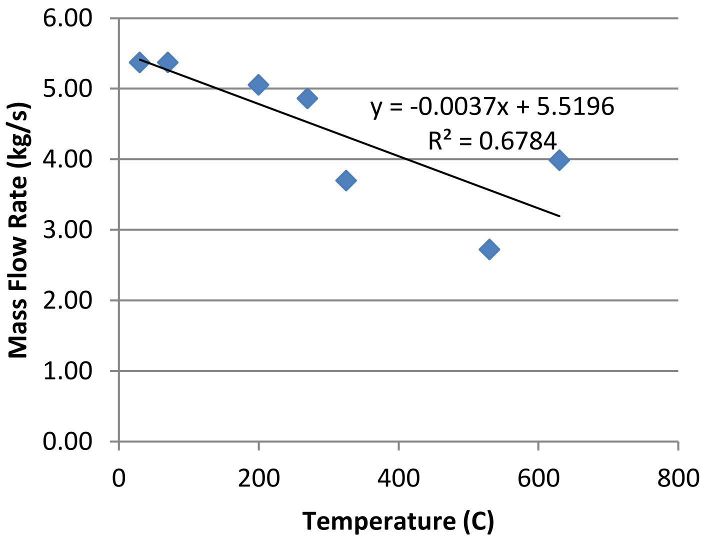
SEM/EDS analysis

Orange-brown dust on receiver walls contains hematite

Summary of On-Sun Test Results

- Achieved average particle outlet temperatures > 700 C
  - Peak particle outlet temperatures > 900 C
- Particle heating up to ~200 – 300 C per meter of drop
- Thermal efficiency ~60% to 80%
- Mesh materials showed signs of wear
  - Use intermittent obstructions instead of continuous array
- Particle mass flow was reduced at higher temperatures
  - Two reasons:
    - Higher particle/wall friction coefficient
    - Narrowing of discharge slot
  - Need active particle mass flow control and monitoring





Summary of On-Sun Test Results

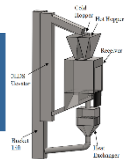
- Particle solar absorptance after ~200 hours of on-sun testing was the same as unused particles
  - Hematite formation on surface being worn off?
- Particle loss was 0.06% of mass flow rate
  - 60% from loss through aperture (5.8 kg/hr)
  - 40% from attrition due to abrasion (3.6 kg/hr)
  - Mitigations
    - Deeper cavity; particle release further from aperture
    - Aperture coverings
    - Wind diverters

Particle loss from aperture during on-sun test

Task Structure and Approach

High Temperature Falling Particle Receiver

FY13: Evaluate alternative designs and concepts to meet SunShot targets
FY14: Construct on-sun prototype capable of 700 C particle temperature
FY15: On-sun testing of free-fall vs. discrete porous structures



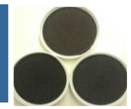
1. Receiver

1.1 – 1.2 Free-Falling Designs

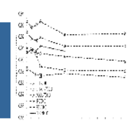
- Sandia

1.3 Discrete-Porous Structure Designs

- Sandia, Georgia Tech

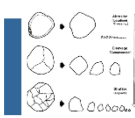


2. Particles



2.1 Radiative Properties

- Bucknell, Sandia



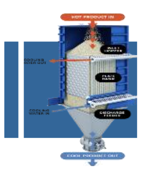
2.2 Durability

- Georgia Tech, DLR, Sandia

3. Balance of System

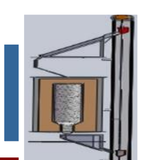
3.1 Thermal Storage Bin

- King Saud University



3.2 Particle/Fluid Heat Exchanger

- Georgia Tech



3.3 Particle Lift System

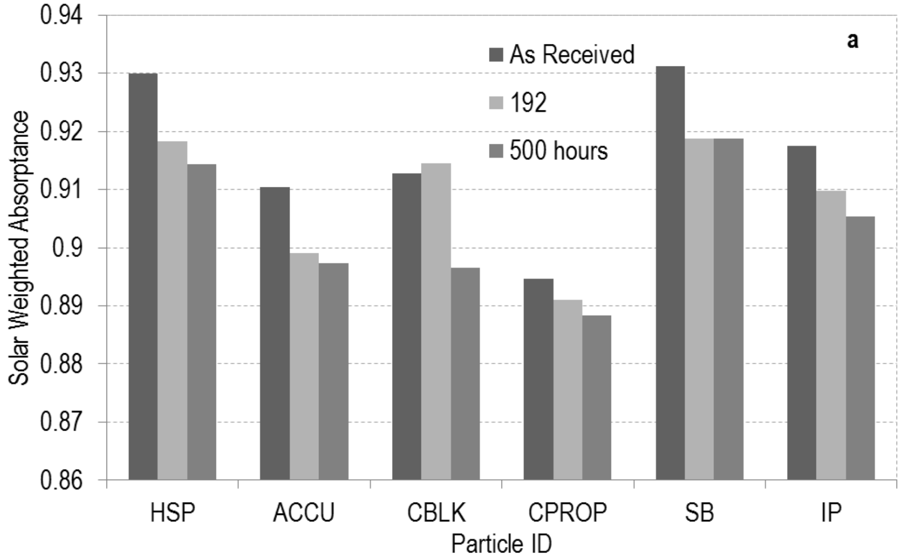
- Georgia Tech, DLR, Sandia

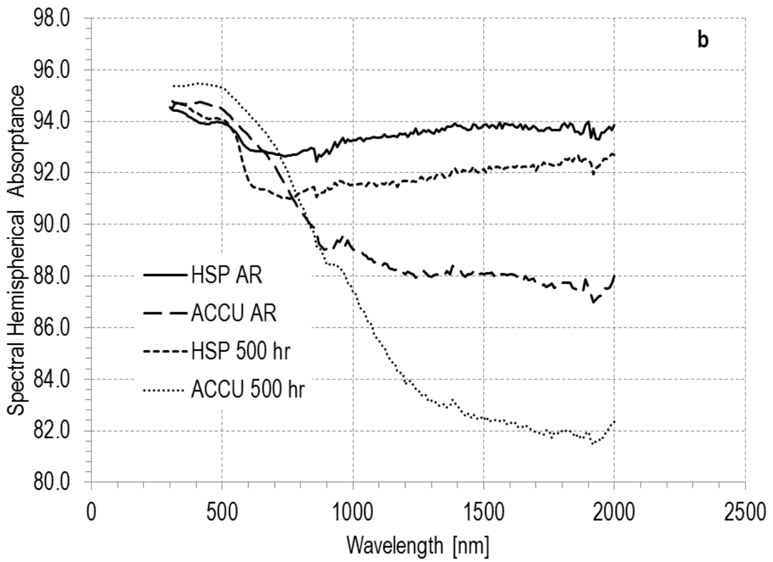
Overall Technical Approach

- Characterize all prospective particles with respect to solar weighted absorptance and thermal emittance
  - As-received and following heating in air at 700˚C
- Investigate the use of thermal or chemical reduction to enhance absorptance and stability.
- Develop a quantitative metric to compare various approaches to particle regeneration
- Synthesize and characterize new particle formulations that are chemically similar to proppants, but using potentially better pigments.

Assessment of Radiative Properties

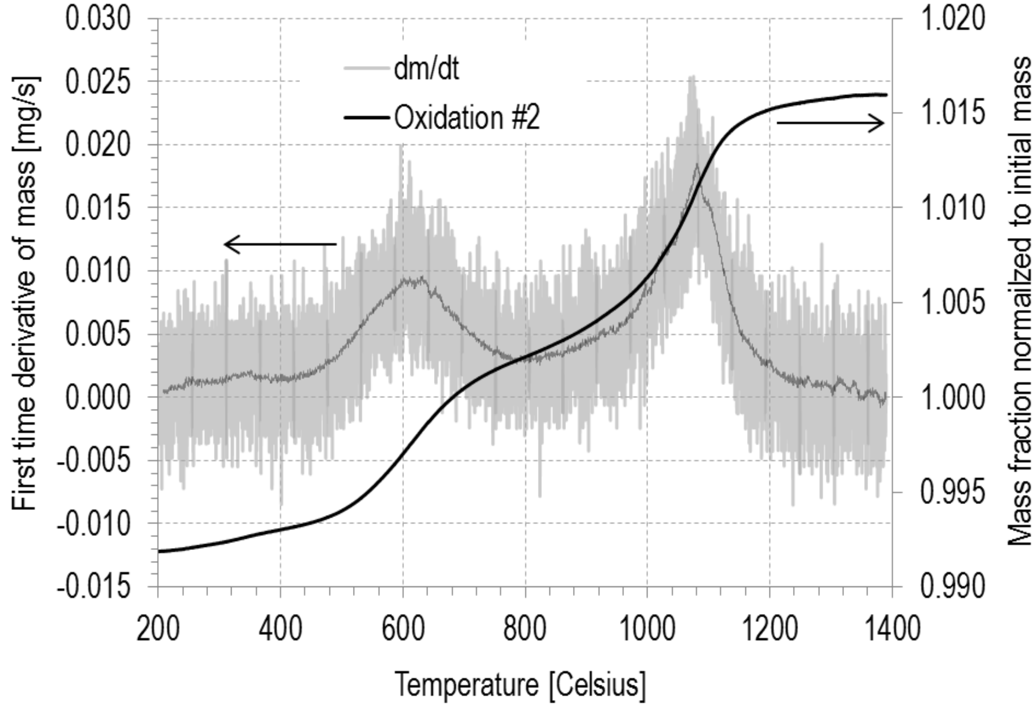
Particle Degradation





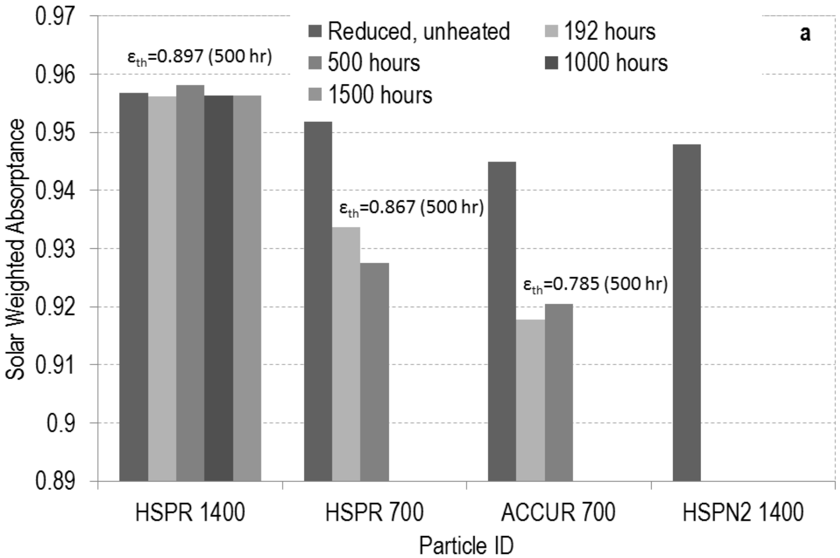
- All commercial particles degrade
- Most of the change is not visible to the eye…occurring in the infrared spectrum

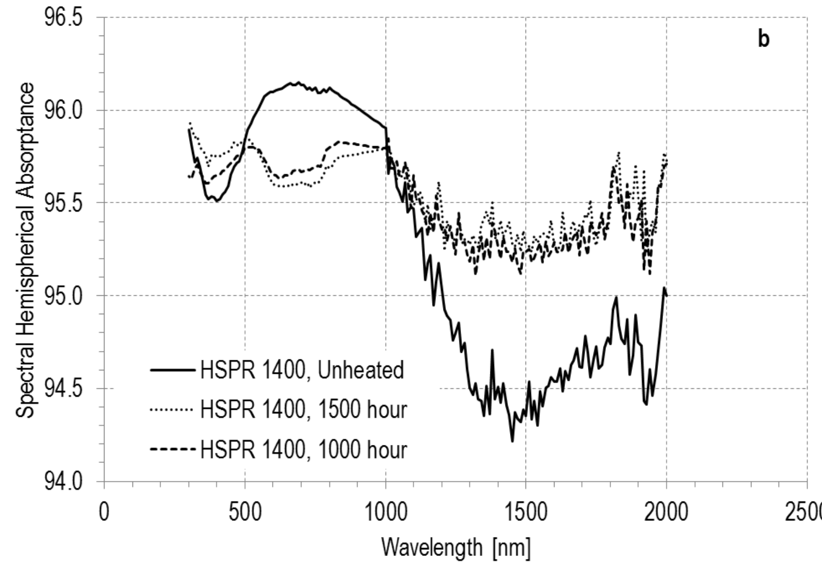
Degradation Mechanism



- Oxidation reactions occur at ~600˚C and ~1100 ˚C
- Reaction at 600˚C causes a change in absorptance

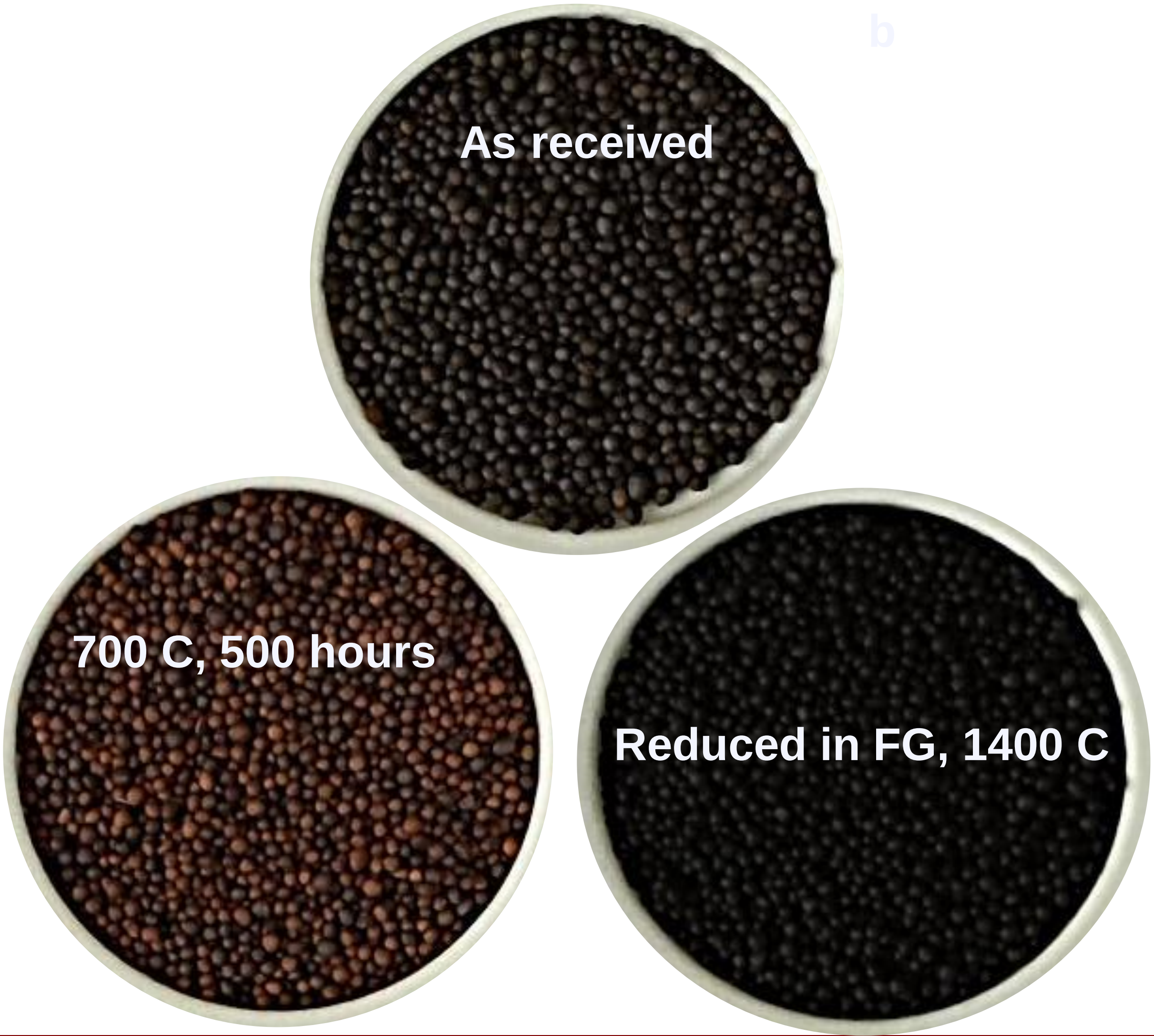
Chemical/Thermal Reduction





- Reducing the particles at high temperature and/or in forming gas can reverse the effects of oxidative degradation
- High temperature chemical reduction enhances the stability of CARBOHSP
- All reduced particles exceed α_s>90% after 500 hours.
- All reduced particles have emittance < 90% after 500 hours.

Particle Degradation and Regeneration



Regeneration Strategies

- All particles can be reduced at high temperature during manufacturing
  - Costs may be low if a “fuel rich” reduction is possible
- Once onsite, there are four regeneration approaches:
  - Chemically reduce in forming gas at 1400˚C in a side-stream reactor
  - Chemically reduce in hydrogen at 1400˚C in a side-stream reactor
  - Chemically reduce in forming gas at 700˚C within the storage system
  - Continuously purge the storage system with nitrogen to inhibit oxidation

Levelized Cost of Absorptance (LCOA)

Levelized Cost of Absorptance

- A quantifiable metric is needed to compare regeneration approaches.
- We adapted Sandia's Levelized Cost of Coating from selective receiver work
- The Levelized Cost of Absortpance (LCOA) is defined as:

$$LCOA = \frac{C}{E_b} = \frac{\sum\left(\frac{IC}{n} + RC + MU + HC\right)}{E_b}$$

What the LCOA Does

- LCOA gives the cost "C" to maintain a certain annual energy production "E_b".
- The plant output is held constant by varying the amount of heliostats used during operation
- Additional heliostats may be built (with associated costs) to offset performance loss due to particle degradation.
- Regeneration cost, "RC", is a function of the cost of each regeneration and regeneration frequency

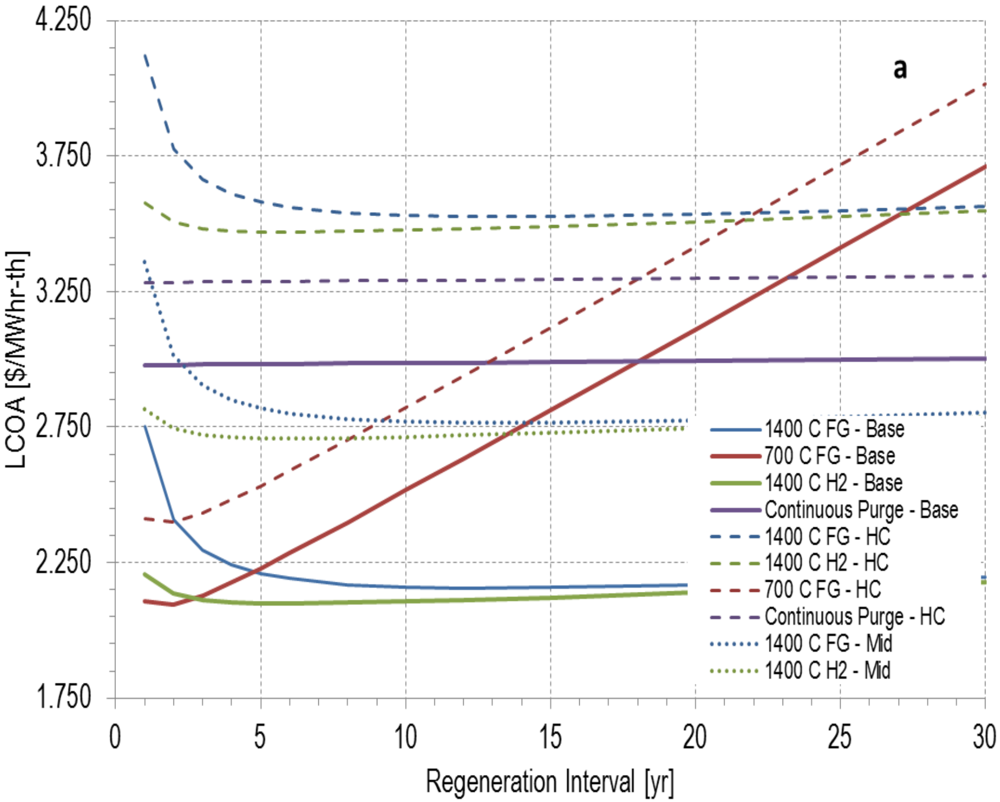
Cost Summary

Regeneration Process	Degradation rate [% pts/yr][1]	Proppant Cost [$/kg]	Material Cost/Regen [$/kg proppant]	Energy Cost/Regen [$/kg proppant]	Capital Cost [$]
1400˚C Reduction in FG	0.6	1.07	0.025-**0.045**	**0.0063**	**1,000,000**-10,000,000
1400˚C Reduction in H_2	0.6	1.07	**0.005**	**0.0063**	**1,000,000**-10,000,000
700˚C Reduction in FG in-situ	9.0	1.07	0.006-**0.011**	0	**0**-2,000,000
Continuous N_2 Purge	0.12	1.07	$473,040-**$946,080**/year[2]	0	**0**-2,000,000

- Proppant capital costs (~$20M) and makeup (10% annually ~$2M) dominate

LCOA Results 1

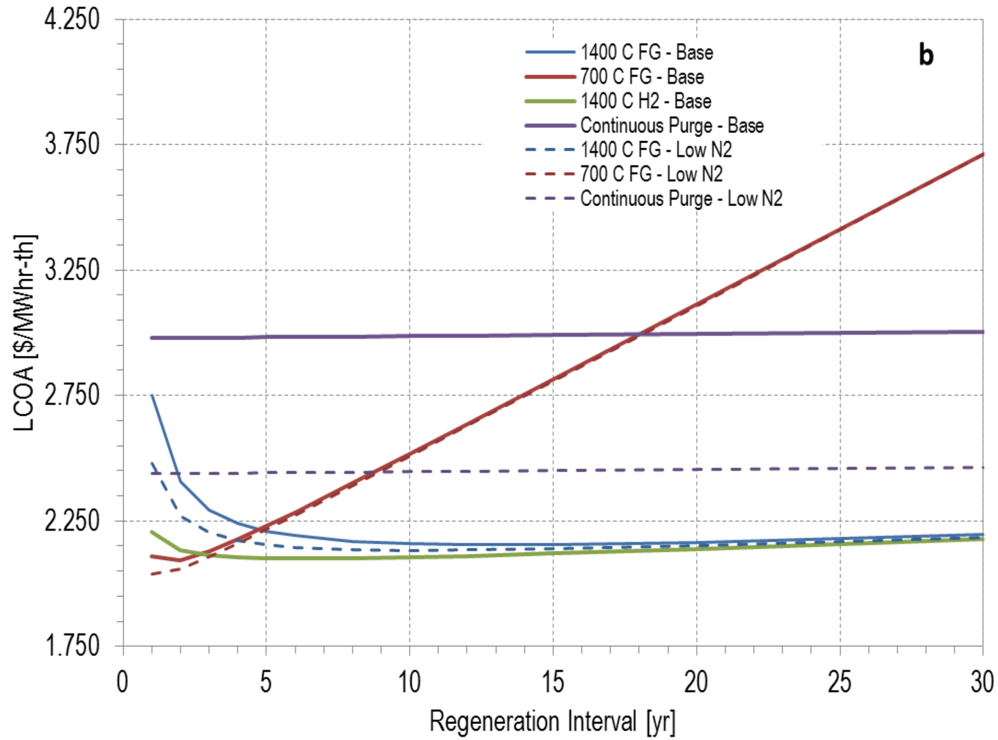
- Baseline values show 700 C and 1400 C chemical reduction to be lowest cost.
- 1400 C hardware costs are uncertain, and likely to be higher than baseline value



700˚C reduction with regeneration period less than 10 years is likely the lowest cost option

LCOA Results II

- Lowering the cost of nitrogen mainly impacts the continuous purge process
- Doesn't change the conclusion that 700C in situ is likely best.



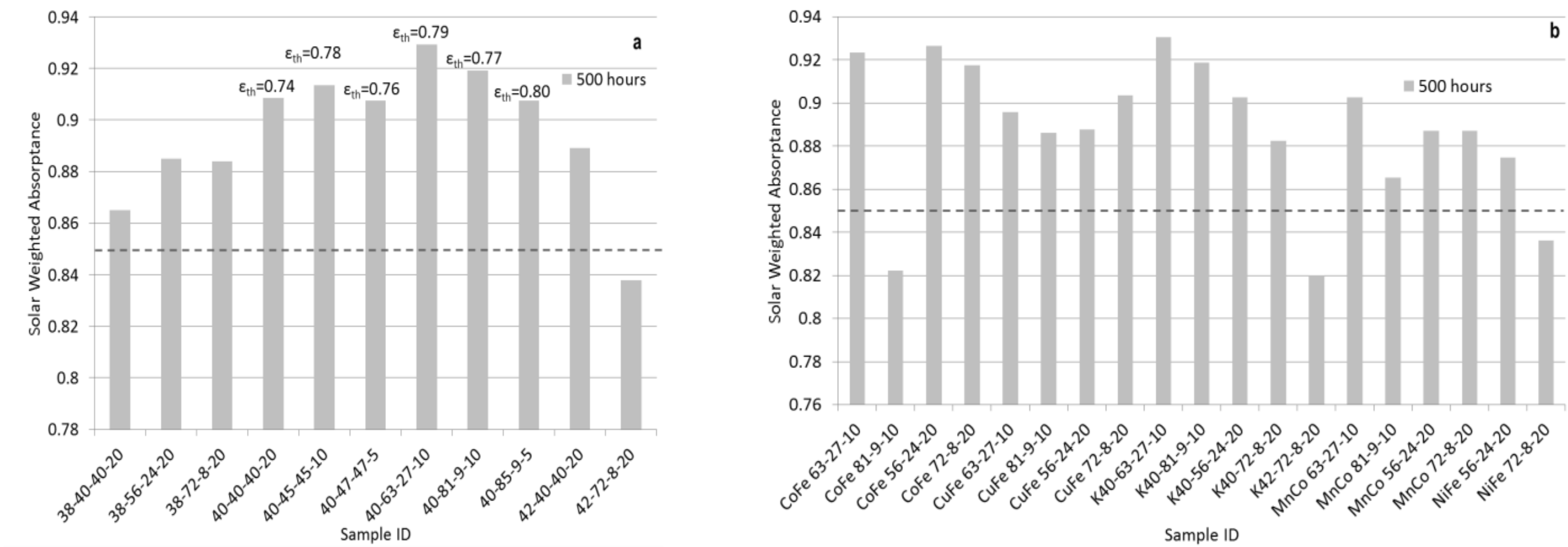
Novel Particle Formulations

Novel Particle Formulations

- 140 unique compositions
- Al_2O_3: 40%-85%
- SiO_2: 10%-40%
- Pigment: 5%-20%
- Commercial pigments and in-house formulations

Pigment Compositions		
$NiFe_2O_4$	$CoCr_2O_4$	CuO
$CoFe_2O_4$	$NiCo_2O_4$	Fe_2O_3
$FeCo_2O_4$	$CuFe_2O_4$	Cr_2O_3
Mn-Fe-O (**K40**)	Cu-Cr-O (**K42**)	NiO
$MnCo_2O_4$	$CuCo_2O_4$	Cu-Cr-Fe-O (**K38**)
$CrCo_2O_4$	$NiCr_2O_4$	

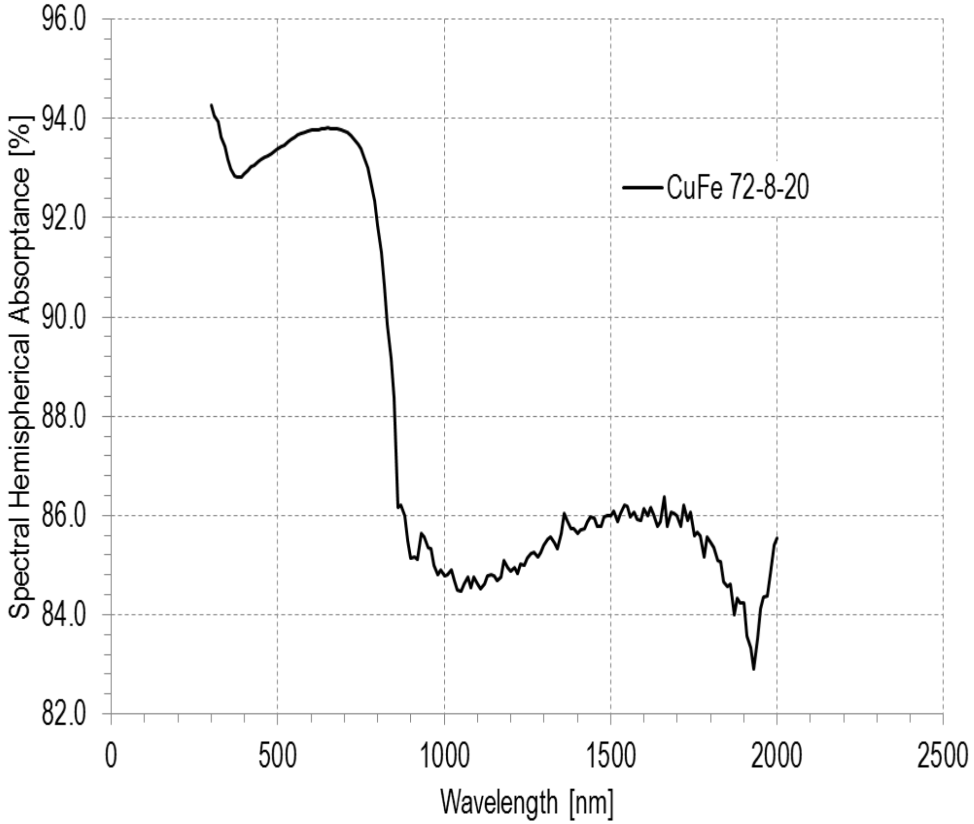
Properties of New Materials



- 11 materials (four pigments) achieve >90% absorptance after 500 hours
- Thermal emittance for K40 < 90% after 192 hours

Selectivity

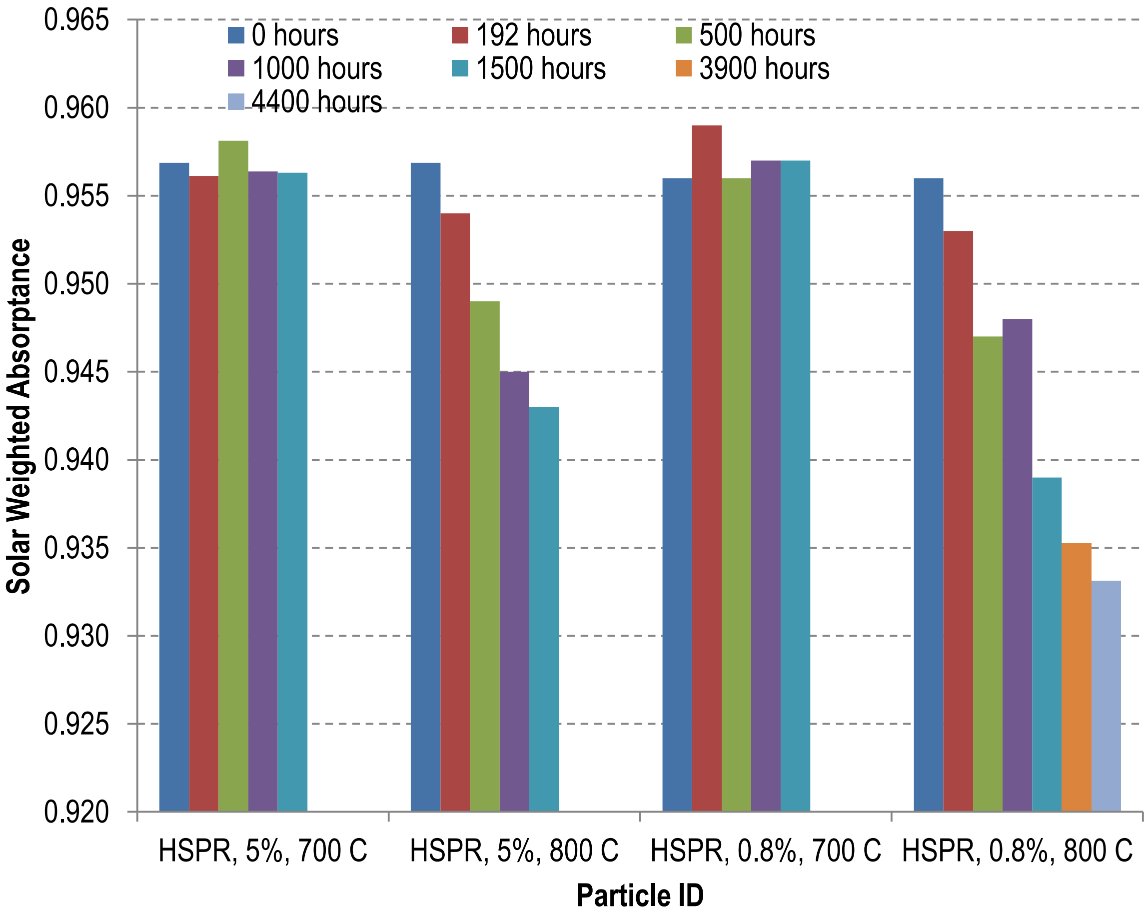
- Some of the materials that we synthesized are solar selective.
- The degree of selectivity is typically not large.



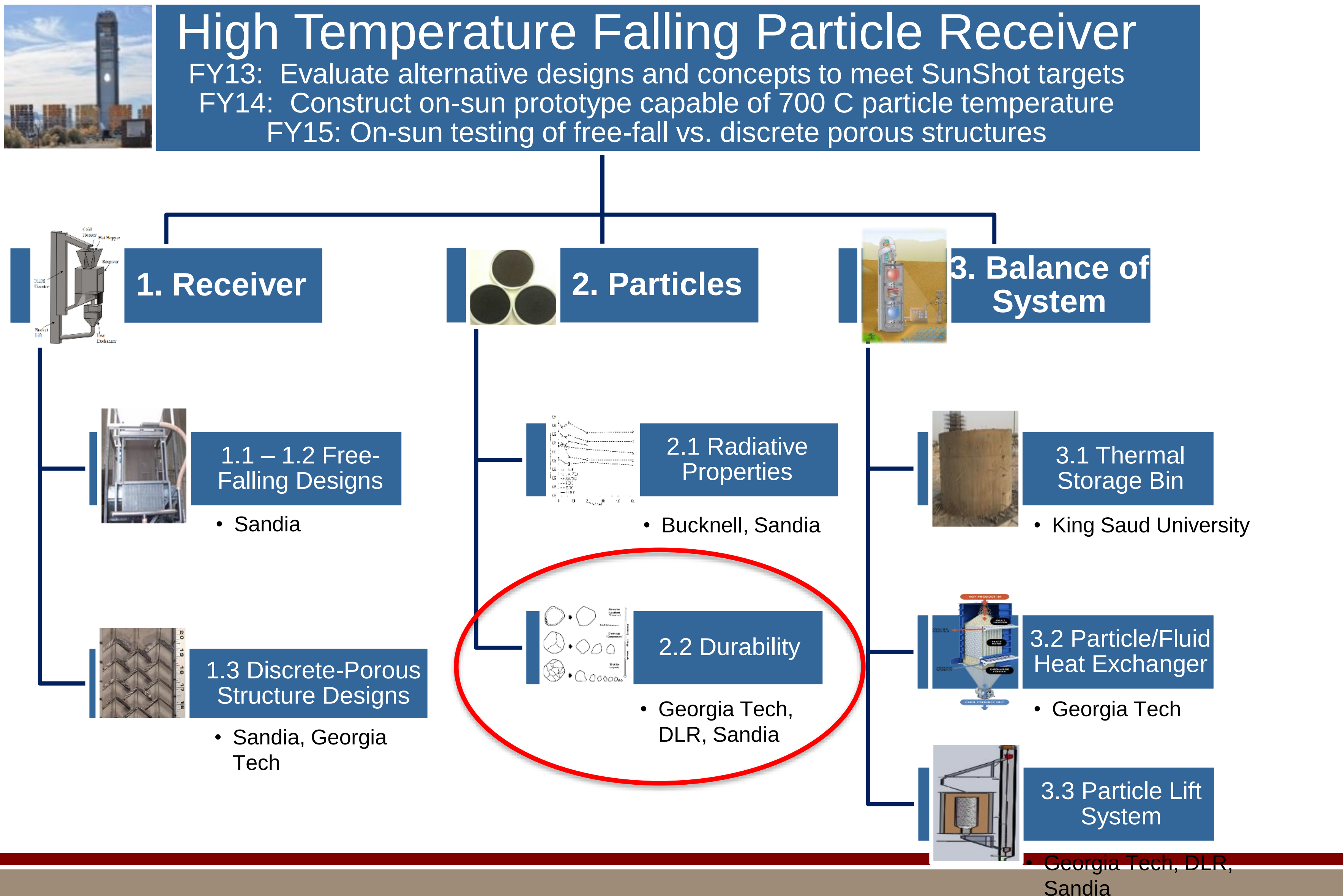
800ºC Operation and Forming Gas Composition (Phase 3)

Oxidation Temperature and FG Composition

- These proppants were all HSP reduced at 1400˚C in forming gas consisting of some percentage of hydrogen (either 5% or 0.8%) in nitrogen. The oxidation temperature is either 800˚C or 700˚C
- Reducing at 0.8% FG is stable at 700˚C
- No formulations are stable at 800˚C out to 4400 hours, although the degradation rate decreases with exposure duration.



Task Structure and Approach



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)

Attrition found to be 10^{-5} – 10^{-4}% of mass flow.

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.

Sintering Potential

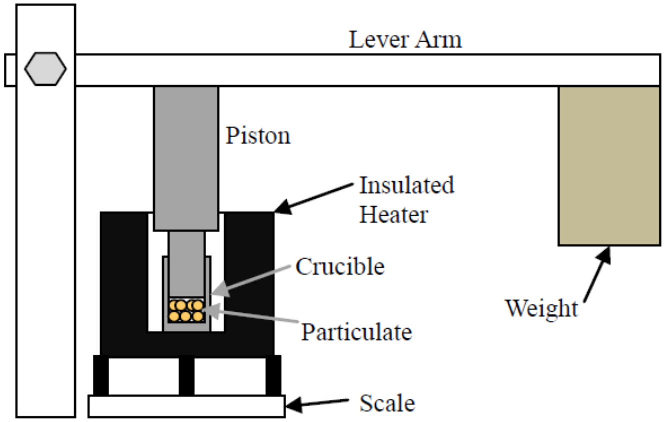


Figure 2. Diagram of Experimental Setup

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

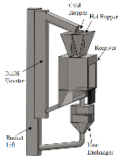
Al-Ansary et al., "Characterization and Sintering Potential of Solid Particles for Use in High Temperature Thermal Energy Storage System," SolarPACES 2013

Sandia National Laboratories

Task Structure and Approach

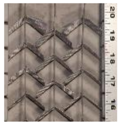
High Temperature Falling Particle Receiver

FY13: Evaluate alternative designs and concepts to meet SunShot targets
FY14: Construct on-sun prototype capable of 700 C particle temperature
FY15: On-sun testing of free-fall vs. discrete porous structures

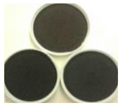


1. Receiver

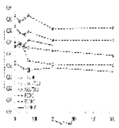
1.1 – 1.2 Free-Falling Designs
- Sandia



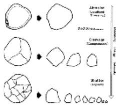
1.3 Discrete-Porous Structure Designs
- Sandia, Georgia Tech



2. Particles



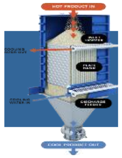
2.1 Radiative Properties
- Bucknell, Sandia



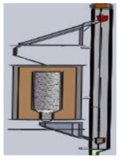
2.2 Durability
- Georgia Tech, DLR, Sandia

3. Balance of System

3.1 Thermal Storage Bin
- King Saud University



3.2 Particle/Fluid Heat Exchanger
- Georgia Tech



3.3 Particle Lift System
- Georgia Tech, DLR, Sandia

Design Concepts

Sandia National Laboratories

Design Basis	Design Code	Advantages	Disadvantages	Assessment
Structural	S1: Steel or metal frame	Relatively inexpensive	• Common metallic materials soften at target temperatures • Thermal expansion can cause adverse cycling effects	Not suitable – Does not meet high-temperature requirements of Milestone 3.1.1
	S2: Exotic metal frame	Withstands high-temperatures	• Expensive • Thermal expansion an issue	Not suitable – Does not help meet cost targets
	S3: Layers of firebrick + reinforced concrete	• Common and inexpensive • Structurally sound	Poor insulation	Not suitable – Not expected to meet heat loss limit of Milestone 3.1.1
	S4: Layers of insulating firebrick + reinforced concrete	High thermal insulation	• Strength can be an issue • Using insulating firebrick alone for insulation is costly	Not suitable – Strength is questionable; does not help meet cost targets
	S5: Layers of firebrick + insulating concrete + reinforced concrete	• Common and inexpensive • Acceptable strength	Insulation acceptable but not optimal	Warrants further investigation
	S6: Layers of insulating firebrick + insulating concrete + reinforced concrete	• Common • Acceptable strength • Superior insulation	Relatively higher cost that S5.	Warrants further investigation
Geometric	G1: Rectangular shaped bin	Easy to construct, instrument and test	Corners may suffer excessive stresses	Warrants further investigation
	G2: Round shaped bin	More care needed in	High structural integrity	Warrants further

Review of Phase I Findings

Experiments on a rectangular-shaped TES bin showed that:

- Steady-state energy loss was ~4.4% for a 24-hour period.
- Materials used for construction of the walls performed well structurally.

Takeaways from the testing campaign were:

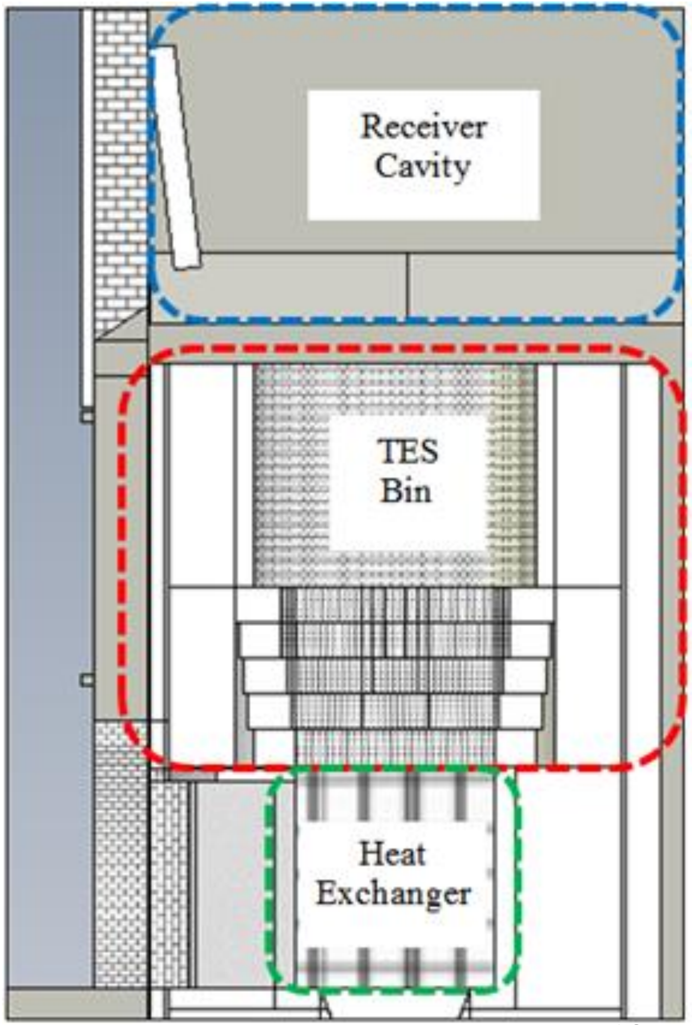
- A cylindrical-shaped TES bin would be more representative of commercial scale applications
- Energy loss from a TES bin is transient and cyclic in nature, and it is necessary to estimate energy loss in this manner.

Phase 2 Approach

- Perform ground-based testing of a cylindrical TES bin similar to the RTV TES bin.
- Monitor the construction and material costs to use them later to estimate the cost of TES per kWh (thermal).
- Model the transient cyclic behavior of the RTV TES bin to see whether actual energy loss departs significantly from steady-state energy loss.

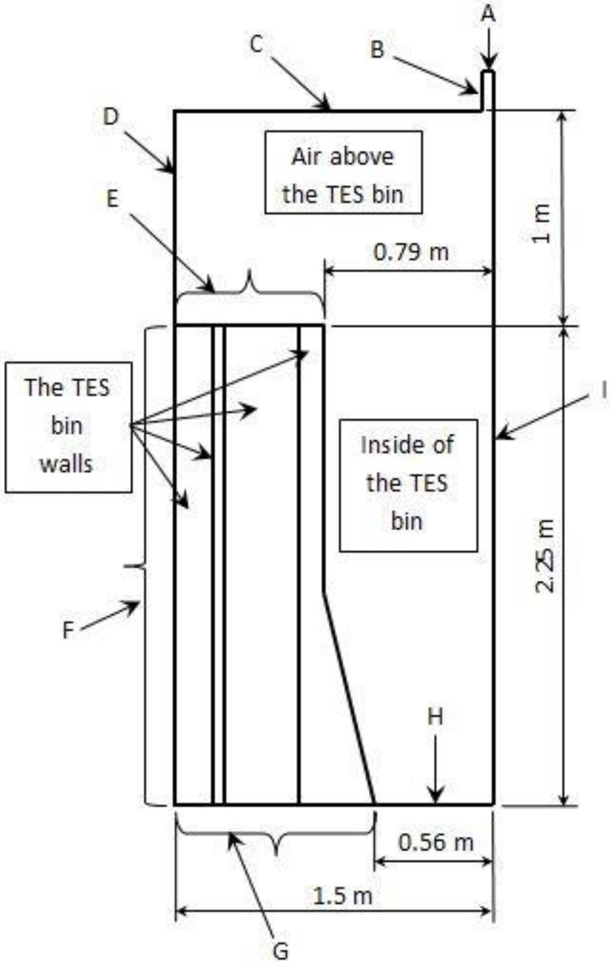
Phase 2 Results: Modeling of RTV TES Bin

- Preliminary RTV TES bin included four layers:
  - 4”-layer of insulating firebrick
  - 16”-layer of perlite concrete
  - 1”-layer of expansion board
  - 8”-layer of reinforced concrete
- The narrowing section in the bottom has the same three outer layers, while additional insulating firebrick layers are added on the inside.



Phase 2 Results: Modeling of RTV TES Bin

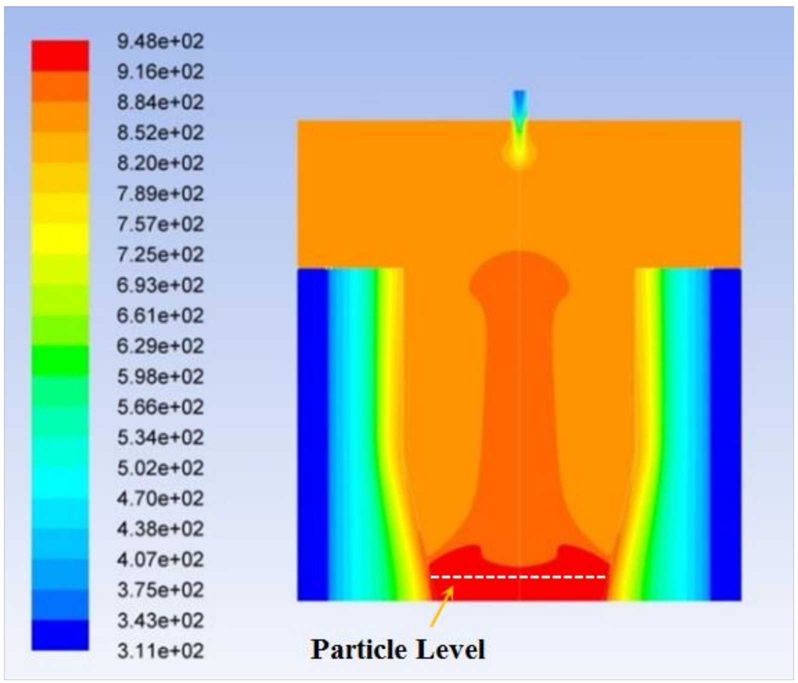
- Volume-of-fluid approach was used.
- Model took advantage of axisymmetry to reduce computational time.
- Carbo Accucast ID50K particles were assumed to enter from Port A at 700 C for 7 hours (**charging phase**)
- Particles leave from Port H during the same period, and continue to leave for 5.25 extra hours (**discharging phase**).
- Ambient air was assumed to leak from Port A once charging of particles stops.
- Two full days (cycles) were simulated.

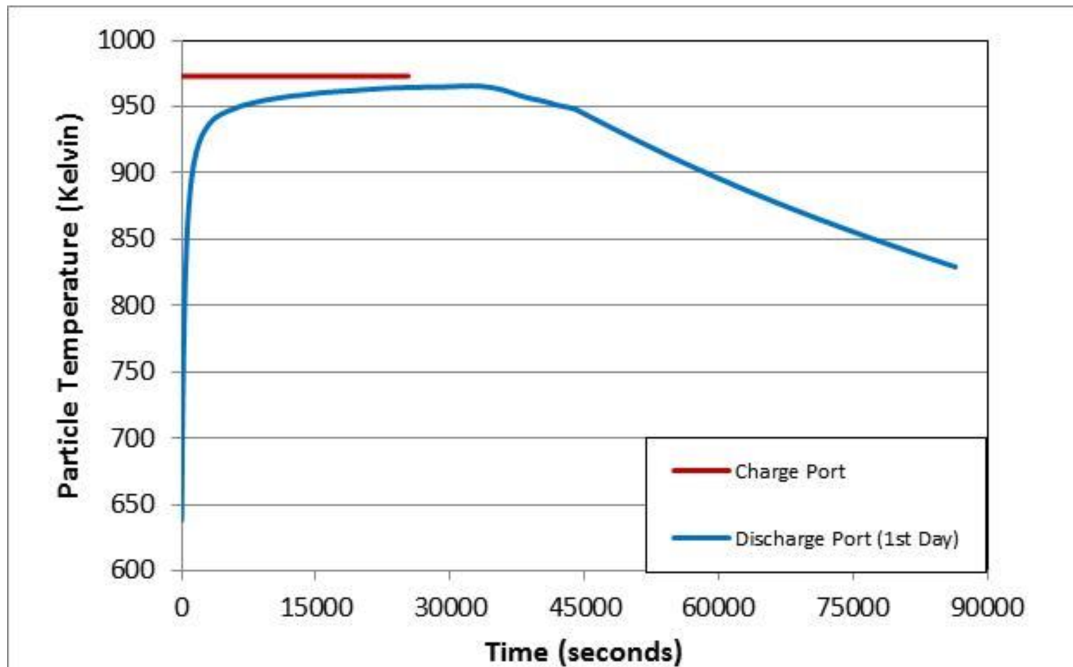


Phase 2 Results: Modeling of RTV TES Bin

Simulation of 1st day of operation showed that:

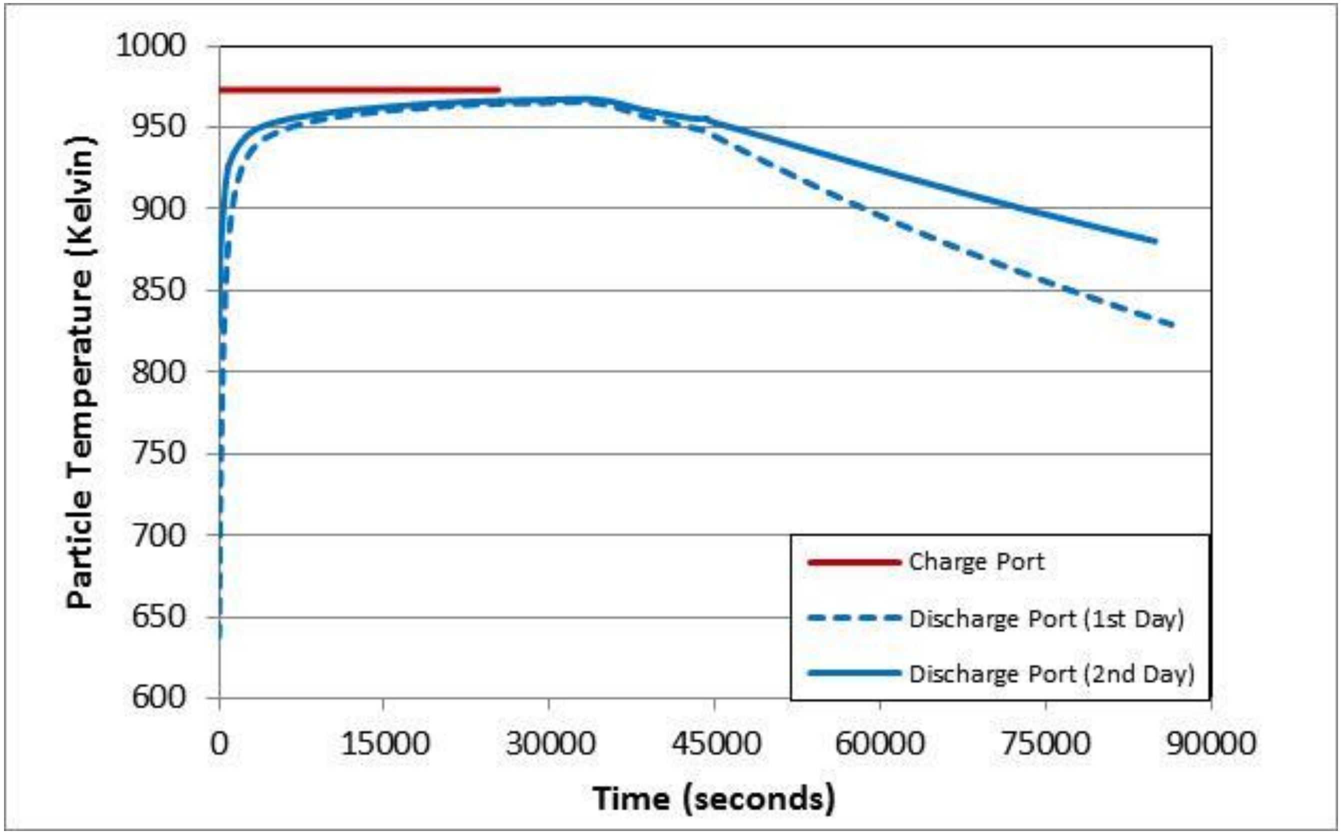
- Particle temperature increases quickly.
- Temperature remains high for a few hours after charging ends.
- Leakage of air causes vigorous natural convection currents





Phase 2 Results: Modeling of RTV TES Bin

- Simulation of 2nd day included very limited leakage of air.
- Temperature profile improved significantly.
- Energy loss was found to be 3.3%.



Phase 2 Results: TES Cost Breakdown

- Table shows actual costs of building the ground-based TES bin.

Cost Item	Cost (in US Dollars)
Reinforced concrete (including plywood for forming)	4,900
Perlite concrete	4,900
Insulating firebrick	8,700
Miscellaneous items	2,900
CARBO Accucast ID50K (7.8 tons to fill TES bin)	12,900
TOTAL COST	34,300

- Cost for this small bin is $33.7/kWh(th).

Phase 2 Results: TES Cost Breakdown

- TES bin in a 100-MW utility-scale facility will have 1/8 the surface-to-volume ratio.
- Cost will drop to $13.6/kWh(th).
- Calculation includes drop in price of Carbo Accucast ID50K for large orders (as quoted by vendor).
- Calculation does not include reduction in price due to:
  - Wholesale purchase of materials.
  - Mechanized mixing and casting of concrete.
  - Optimized labor sourcing.
- $13.6/kWh(th) represents an upper cost limit.

Phase 3 Results: Ground-Based Testing

- A ground-based cylindrical TES bin was built with the same radial dimensions of the actual RTV TES bin.
- An electric heater was placed in the center of the bin.
- More than 50 thermocouples measure the temperatures at different radial and circumferential locations.
- Thermal conductivity of different layers measured

Thermal Conductivity Measurements

Temp. setting	Insulating firebrick, FB			Perlite concrete, PC			Expansion joint, EJ		
	Temp. [°C]	k [W/m.°C]	Standard deviation of the means [%]	Temp. [°C]	k [W/m.°C]	Standard deviation of the means [%]	Temp. [°C]	k [W/m.°C]	Standard deviation of the means [%]
300 °C	268	0.218	2.6	162	0.113	2.4	60.9	0.0455	1.5
500 °C	438	0.169	2.3	245	0.114	2.2	70.1	0.0466	1.5
700 °C	641	0.226	2.2	363	0.146	2.1	105	0.0514	1.5

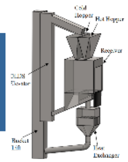
Effective thermal conductivity of reinforced concrete estimated at 1.91 W/m-K

RTV Testing

Task Structure and Approach

High Temperature Falling Particle Receiver

FY13: Evaluate alternative designs and concepts to meet SunShot targets
FY14: Construct on-sun prototype capable of 700 C particle temperature
FY15: On-sun testing of free-fall vs. discrete porous structures



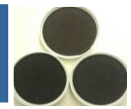
1. Receiver

1.1 – 1.2 Free-Falling Designs

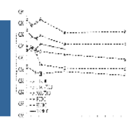
- Sandia

1.3 Discrete-Porous Structure Designs

- Sandia, Georgia Tech

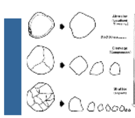


2. Particles



2.1 Radiative Properties

- Bucknell, Sandia



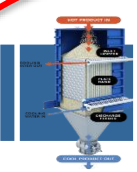
2.2 Durability

- Georgia Tech, DLR, Sandia

3. Balance of System

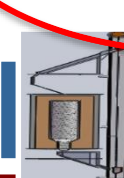
3.1 Thermal Storage Bin

- King Saud University



3.2 Particle/Fluid Heat Exchanger

- Georgia Tech



3.3 Particle Lift System

- Georgia Tech, DLR, Sandia

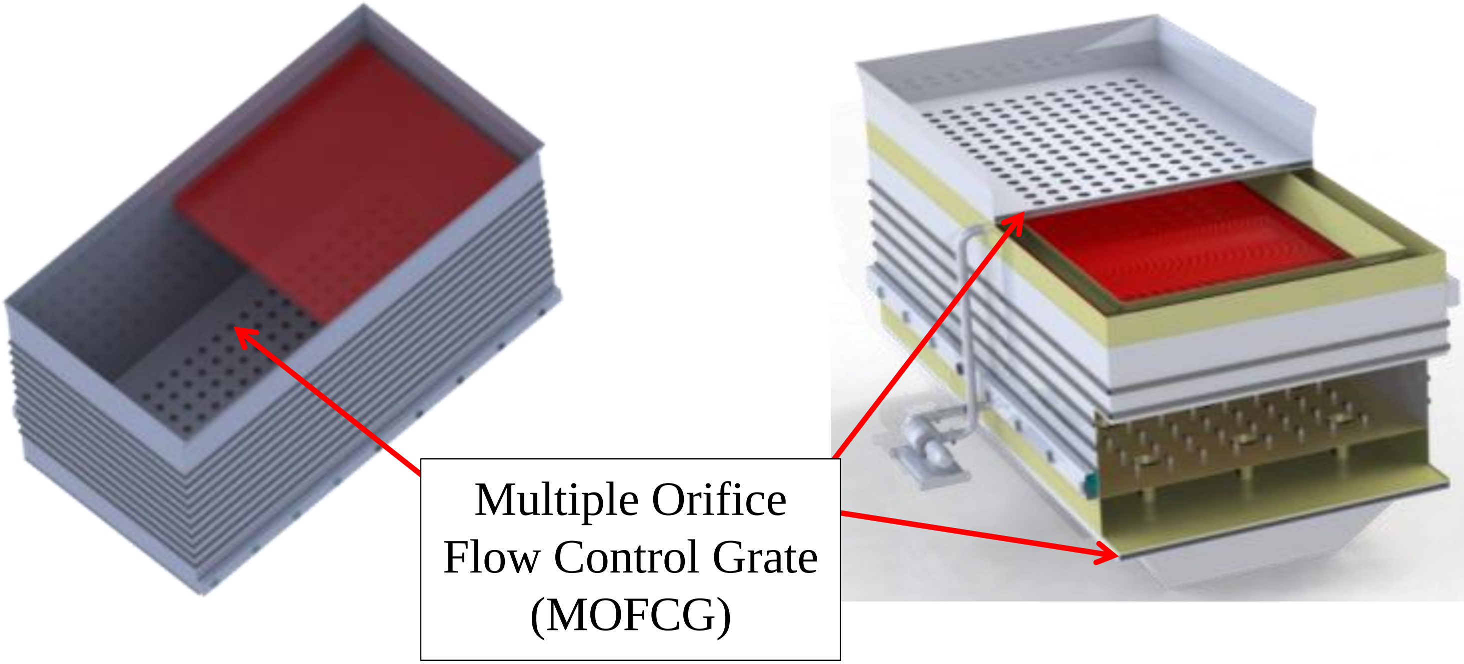
Task 3.2 Particle to Working Fluid Heat Exchanger (Georgia Tech)

Phase 1

- Developed one promising design: Serpentine Finned Tube (SFT)
- Completed Intermediate Scale Experiment (ISE) for SFT
- Developed Performance and Cost Models

- Phase 2: rank four alternative PFHX designs:
- (1) serpentine finned-tube (SFT) with particulate plug flow
- (2) fluidized bed (FB) PFHX,
- (2, alt) finned tubed FB-FT-HX (added recently)
- (3) free-surface flow, zig-zag (ZZ) PFHX
- (4) parallel pillow-plate (PP) PFHX also with plug flow.

Task 3.2 Particle to Fluid HX (preferred)



Left: Serpentine Finned Tube (SFT) HX (most tubes omitted for clarity;
Right: Fluidized Bed (FB) PFHX

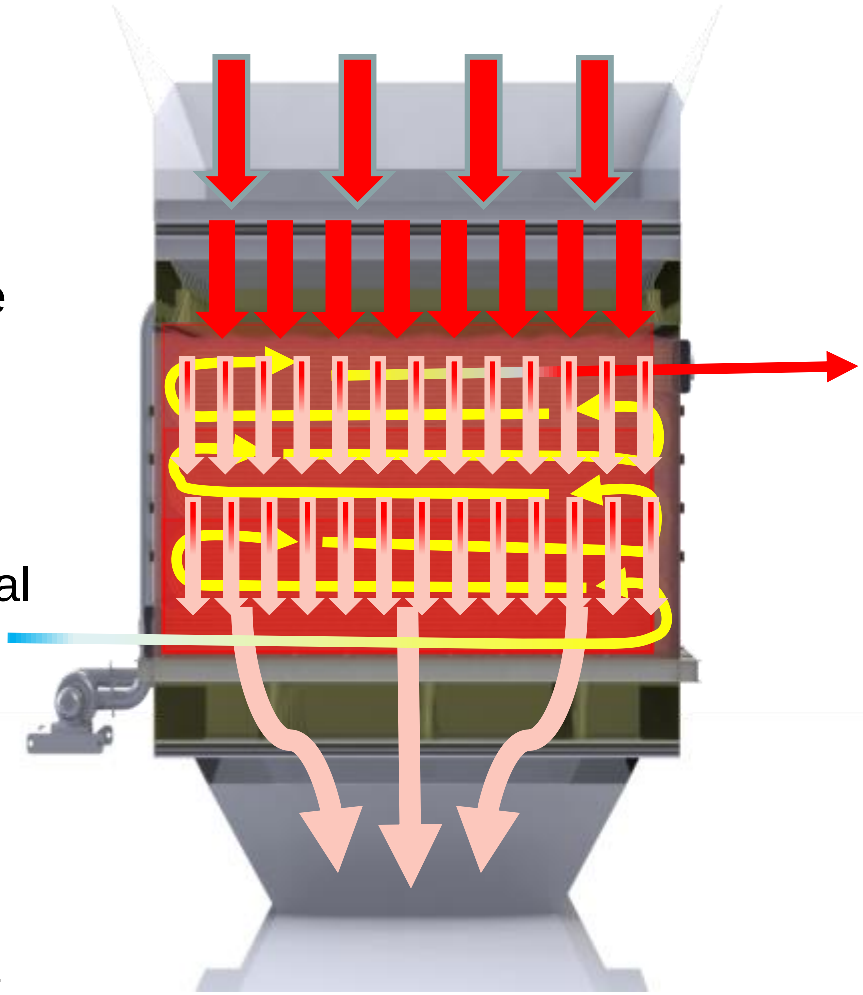
Multiple Orifice Flow Control Grate (MOFCG)
significantly aids integration and likely performance

Task 3.2 Particle to Fluid FB-HX (animation)

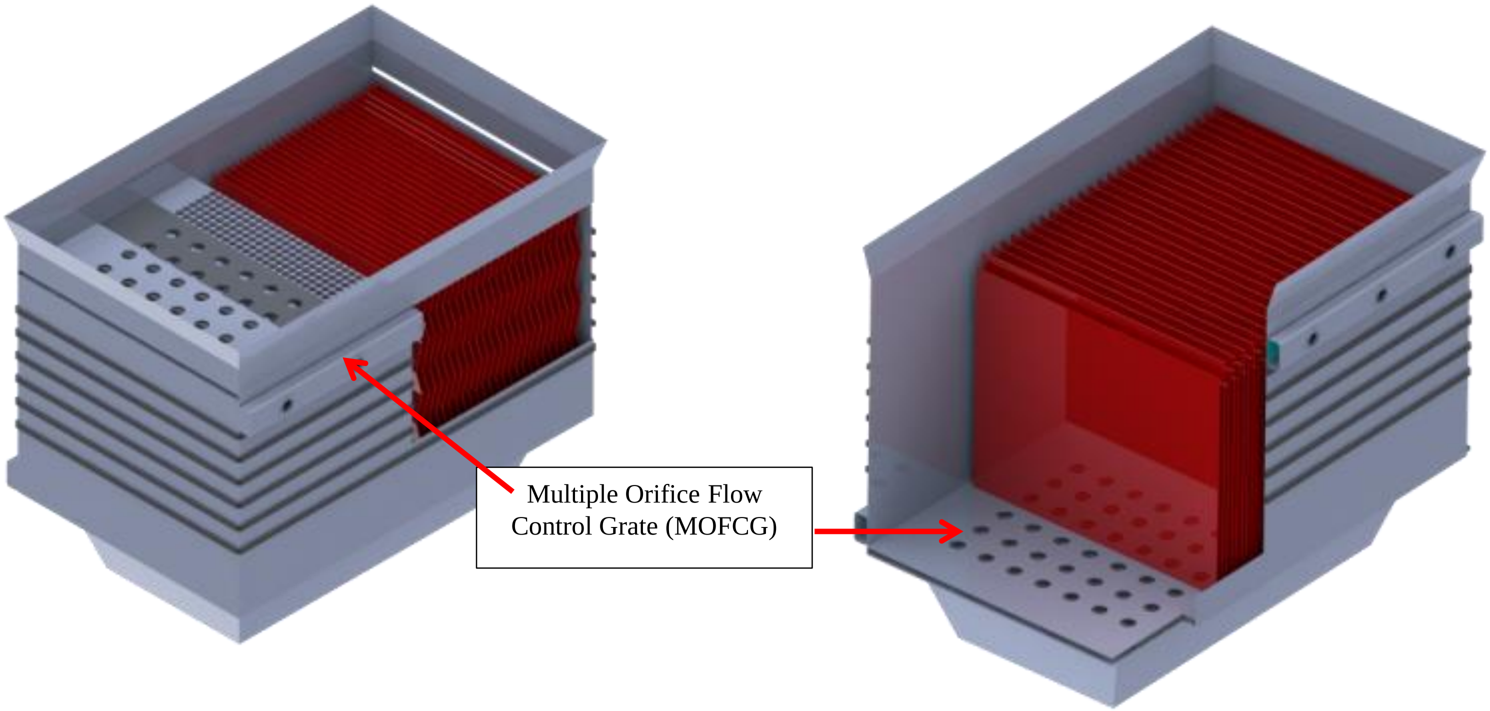
Sandia National Laboratories

Features:

- Upper MOFCG
  - inventory ctrl
  - Uniform inlet
- FB high sand side HTF coefficient
- Serpentine tube
  - Structural
  - Allows thermal expansion
  - Generally CF
  - High HX-eff
- Plenum
- Lower MOFCG
  - Flow control
  - Power output



Task 3.2 Particle to Fluid HX (others)



Left: Zig-Zag (ZZ) trickling flow HX (corrugations exaggerated for clarity)
Right: Parallel Pillow Plate (PP) HX (in section showing plates and MOFCG.

Task 3.2 Particle to Fluid HX, Approach

- Review pertinent Heat transfer (HTF)
  - Technical literature, Commercial literature
  - Cost data
- Develop conceptual designs: all 220 MWth
- Designs for 300 C to 700 C Accucast, with 50 K approach
- Model sand side HTF
- Model fluid side HTF (considering sc-CO2 for now)
- Estimate tubing and structural costs
- Account for fluid side pressure drop (.06 $/kW-hr)
- Account for cost of fluidization (blower at .06 $/kW-hr)
- Assume reasonable econ scenario (0.03 MARR, 30 year life)
- Find optimum designs: balance performance and LCC

Task 3.2 Particle to Fluid HX

Performance modeling

- Vary: tube size, length per pass, number of tubes
- Calculate UA per length: sand side, fluid side, fin efficiency
- Calculate number of passes
- Calculate fluid side pressure drop
- Fluidized bed pressure drop and flow
- Optimize for min LCC

Cost modeling

- Tubing, Structural Frame, MOFCG
- Welds, fabrication
- Blower (high temp assumed)

Task 3.2 Particle to Fluid HX

Overview of sources for cost data:

Details to be presented in upcoming paper(s)

Category	Source	Category	Source
Tubing	Vendor Data	**Construction details**	RS Means DB
Tubing, alt material	NETL indices	**Construction units**	RS Means DB
Equipment	NETL DB	**Fabrication**	Vendor, Ni Inst.
Equipment, material	NETL indices	**Welding**	Vendor, Ni. Inst.
Construction metals	World Steel Prices	**Installed Cost/mass**	Tata Brochure

Task 3.2 Particle to Fluid HX

Design and optimization results:

Include particle properties in footer

Type	$h_{particle}$ W/m²-K	Tube mat	Equip Cost $/kWth	LCC $/kWth	P-Risk	I-Risk	SF-Risk
FB-FT	450	CS/SS	16	33	MOD	MOD	LOW
FB*	600	CS/SS	23	39	HIGH	MOD	LOW
FB**	450	CS/SS	26	46	LOW	MOD	LOW
SFT	101	SS	31	36	MOD	MOD	LOW
ZZHX	400	SS	56	N/A***	HIGH	MOD	MOD
PPHX	100	SS	82	N/A***	LOW	LOW	MOD

FB = fluidized bed, FT = finned tube, SFT = serpentine finned tube, ZZ = zig-zag, PP = pillow plate, HX = heat exchanger

***higher $h_{particle}$, near max; **conservative $h_{particle}$; ***equipment cost too high – LCC not calculated**

P-Risk: performance risk, I-Risk: system integration risk, SF: structural failure risk

Task 3.2 Particle to Fluid HX, Findings

- Candidate technologies ranked by cost of optimized design
- LCC also considered in design
- Designs necessarily achieve high exergy efficiency, 95.3%
- Also assessed risk issues:
  - performance risk
  - system integration risk
  - structural failure risk
- Ranking:
  - Fluidized bed with finned tubes, FB-FT
  - Fluidized bed with bare tubes FB-HX
  - Near passing: Serpentine Finned Tube (SFT)
  - Worthwhile alternative for SNL demo: Solex with tubes

Task Structure and Approach

High Temperature Falling Particle Receiver

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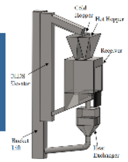
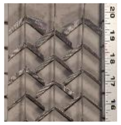


1. Receiver

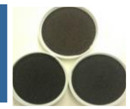
1.1 – 1.2 Free-Falling Designs

- Sandia

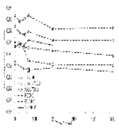


1.3 Discrete-Porous Structure Designs

- Sandia, Georgia Tech

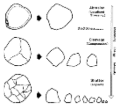


2. Particles



2.1 Radiative Properties

- Bucknell, Sandia



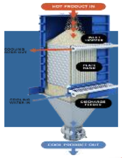
2.2 Durability

- Georgia Tech, DLR, Sandia

3. Balance of System

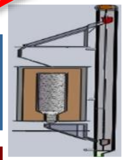
3.1 Thermal Storage Bin

- King Saud University



3.2 Particle/Fluid Heat Exchanger

- Georgia Tech



3.3 Particle Lift System

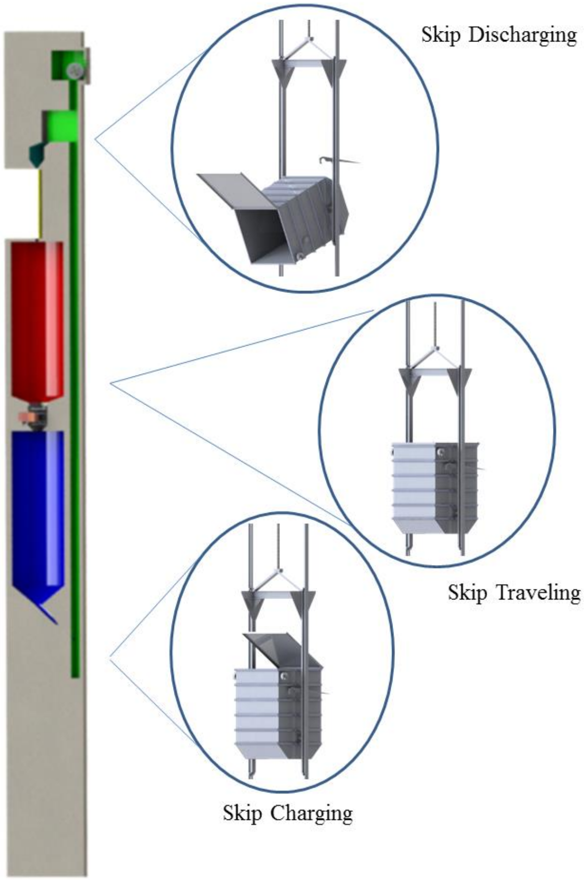
- Georgia Tech, DLR, Sandia

Task 3.3 Particle Tower Lift System

1. Phase 1 Conceptual Designs
2. Phase 2 Design Development, Selection
3. Mechanical Design
4. Efficiency Analysis (80% efficiency projected)
5. Cost Estimation
    - Around 8,700 $/MW-th in for 60 MW-th
    - Around 5,500 $/MW-th in for 460 MW-th
6. Optimization
7. Industrial Reviews (2)
8. Publication (ES2016, others coming)

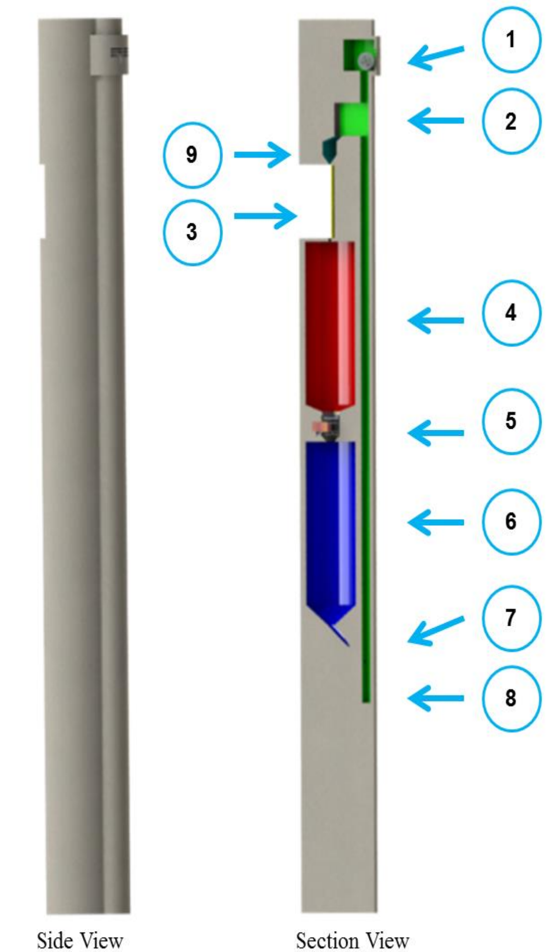
Task 3.3 Particle Lift, Design Overview

- **Insulated Kimberly skip charging, traveling, and discharging**



Task 3.3 Particle Lift, Design Development

- Sketch of 100 MWe, 460 MWth (2.09 solar mux) CRPT



No.	Name
1	Lift Machine Room
2	Lift Discharge Chute
3	Particle receiver
4	High Temperature TES Bin
5	PWF Heat Exchanger
6	Low Temperature TES Bin
7	Lift Charge Chute
8	Lift Shaft
9	Top hopper