An Introduction to Concentrating Solar Technologies at Sandia National Labs

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Seminar, 2 November 2018
New Mexico State University

Sandia National Labs

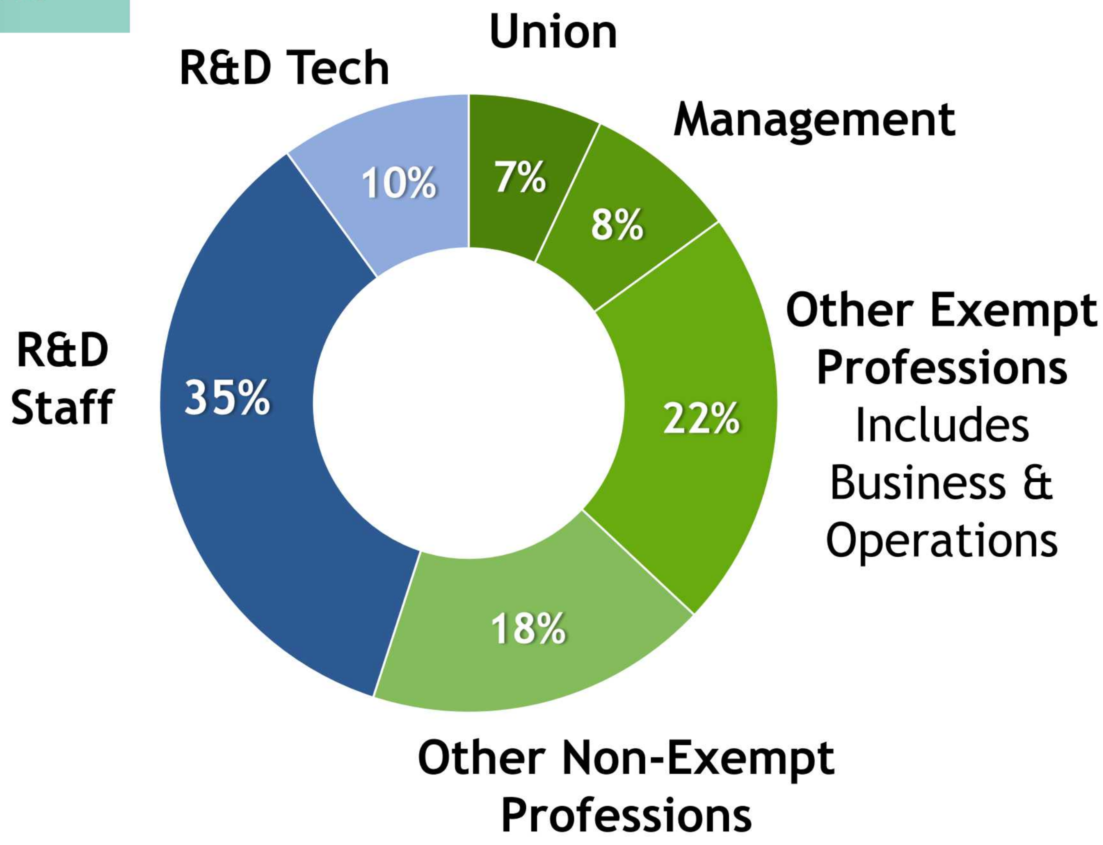
- Sandia is one of 17 National Laboratories

Our Workforce: ~12,000 employees

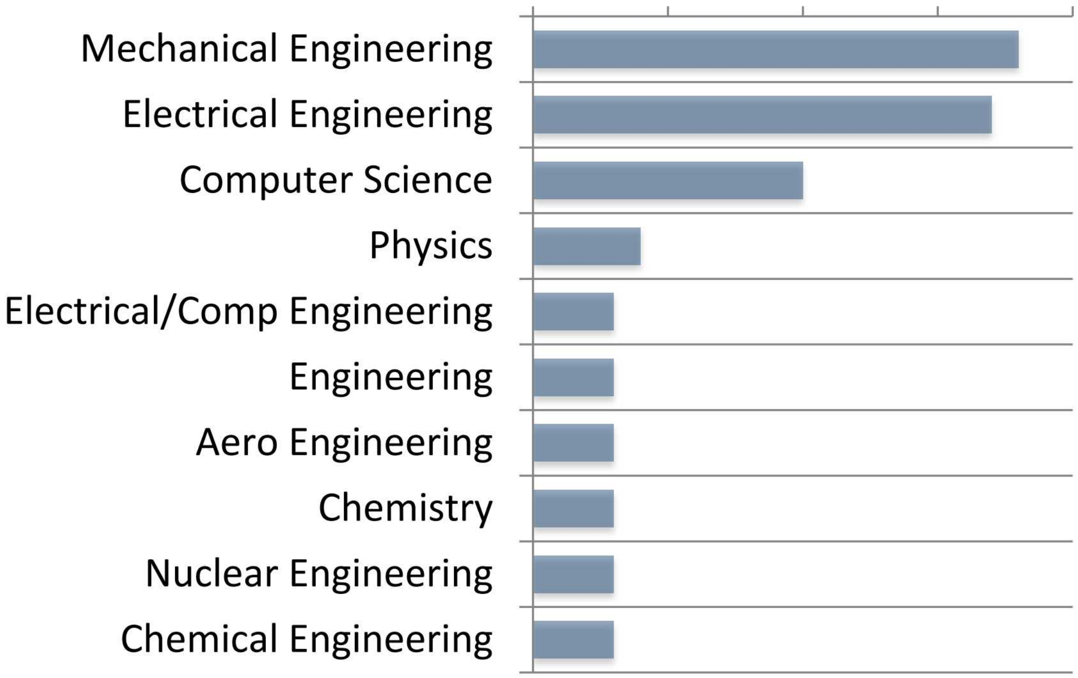
~10,600 Regular employees
~2,000 Temporary employees, students & postdoctoral appointees

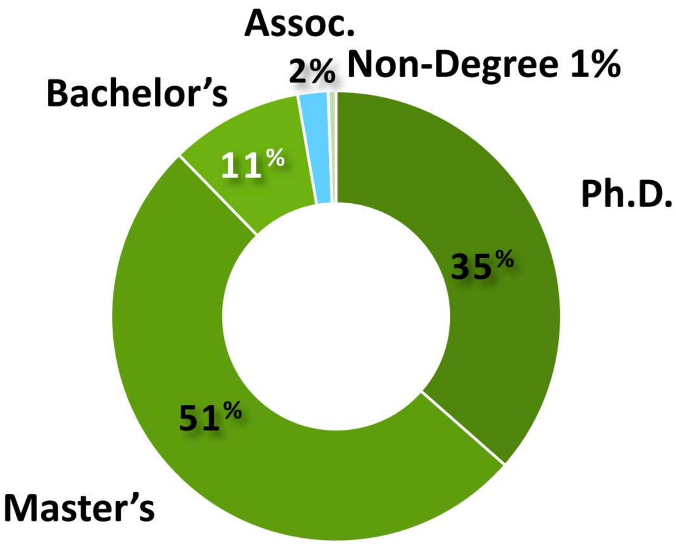
New Mexico Site:
Workforce: ~9,600
R&D employees: ~4,800
(R&D Staff & Technologists)

California Site:
Workforce : ~1,000
R&D employees: ~600
(R&D Staff & Technologists)



R&D by Discipline & Degree





Top 10 job descriptions shown, Regular exempt non-management employees only

Data as of June 30 end of Q3 of the FY17

National Security Mission Areas

Nuclear Deterrence

National Security Programs

Energy & Homeland Security

- Transportation and energy systems
- Renewable systems and energy infrastructure
- Homeland Security
- Cyber and Infrastructure Security

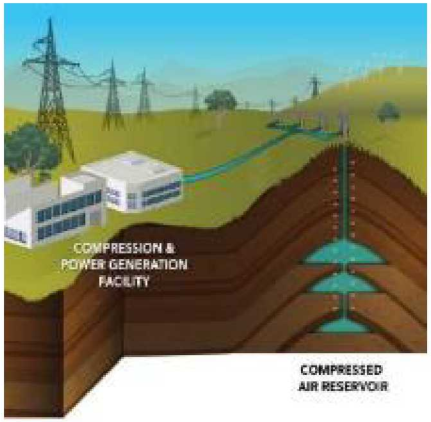
Defense Nuclear Non-Proliferation

Concentrating Solar Power (CSP)

- Intro to CSP
- National Solar Thermal Test Facility
- Materials in CSP
- CSP Research at Sandia

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/kWhe - $1.00/kWhe
  - Compressed air and pumped hydro – geography and/or resource limited



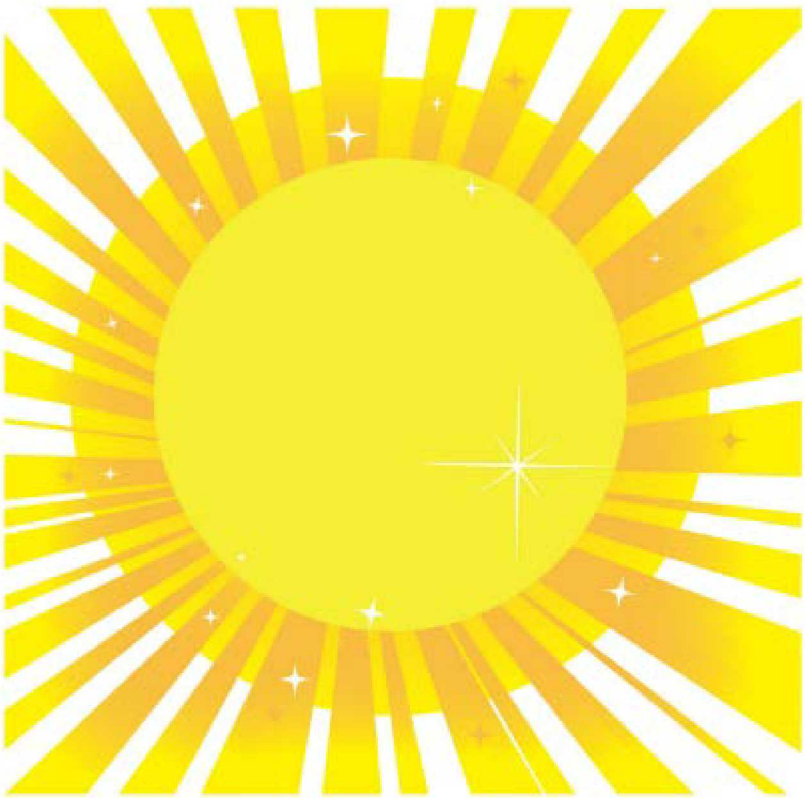
Need

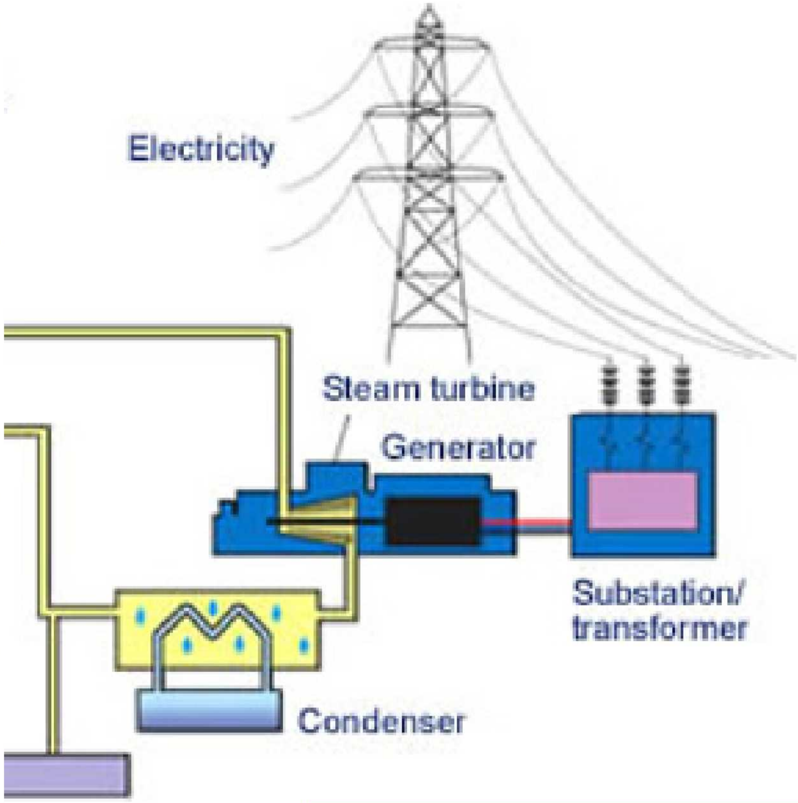
- Renewable energy technology with reliable, efficient, and inexpensive energy storage

→ Concentrating solar power (CSP) with thermal energy storage

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

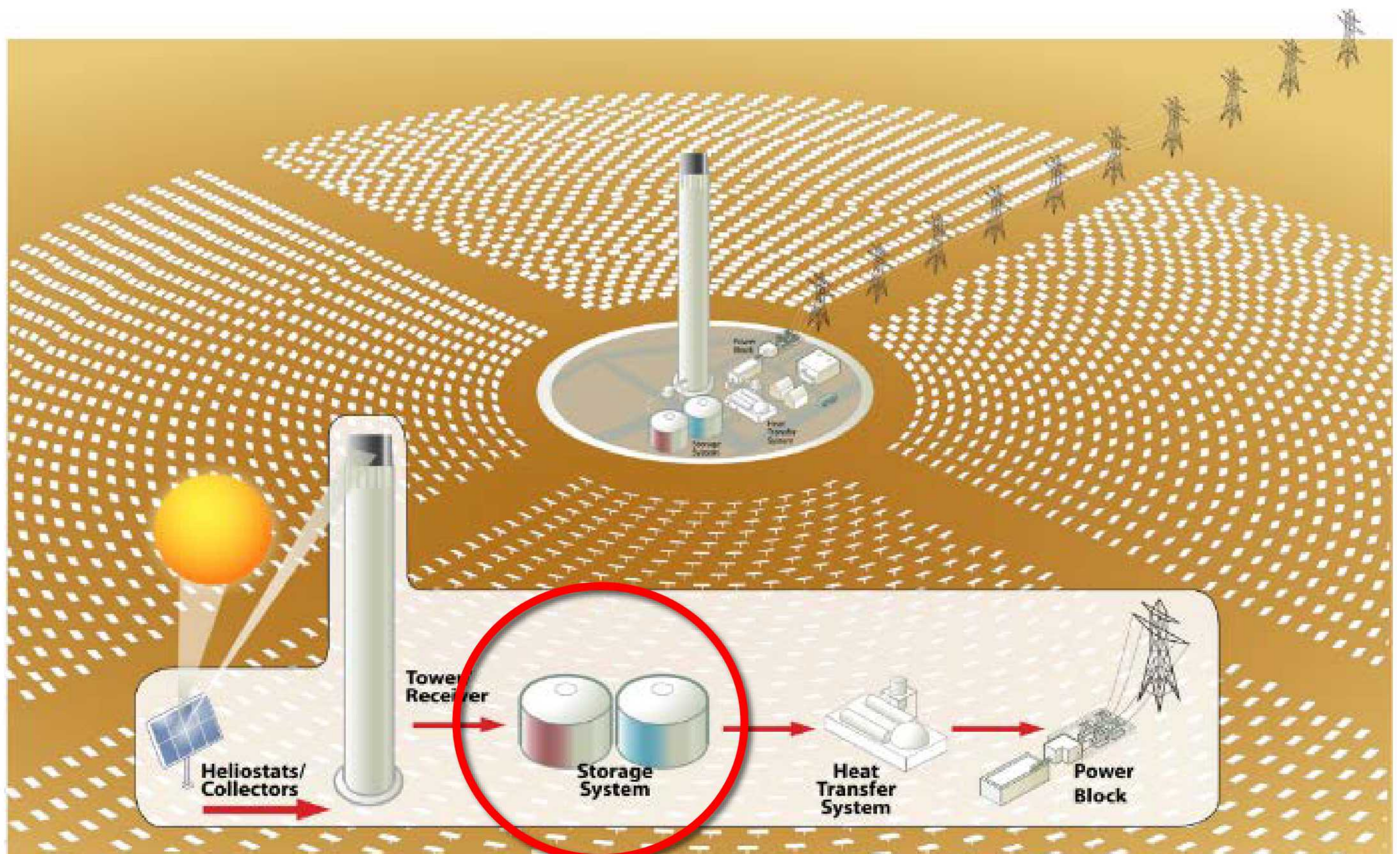




Coal-Fired Power Plant

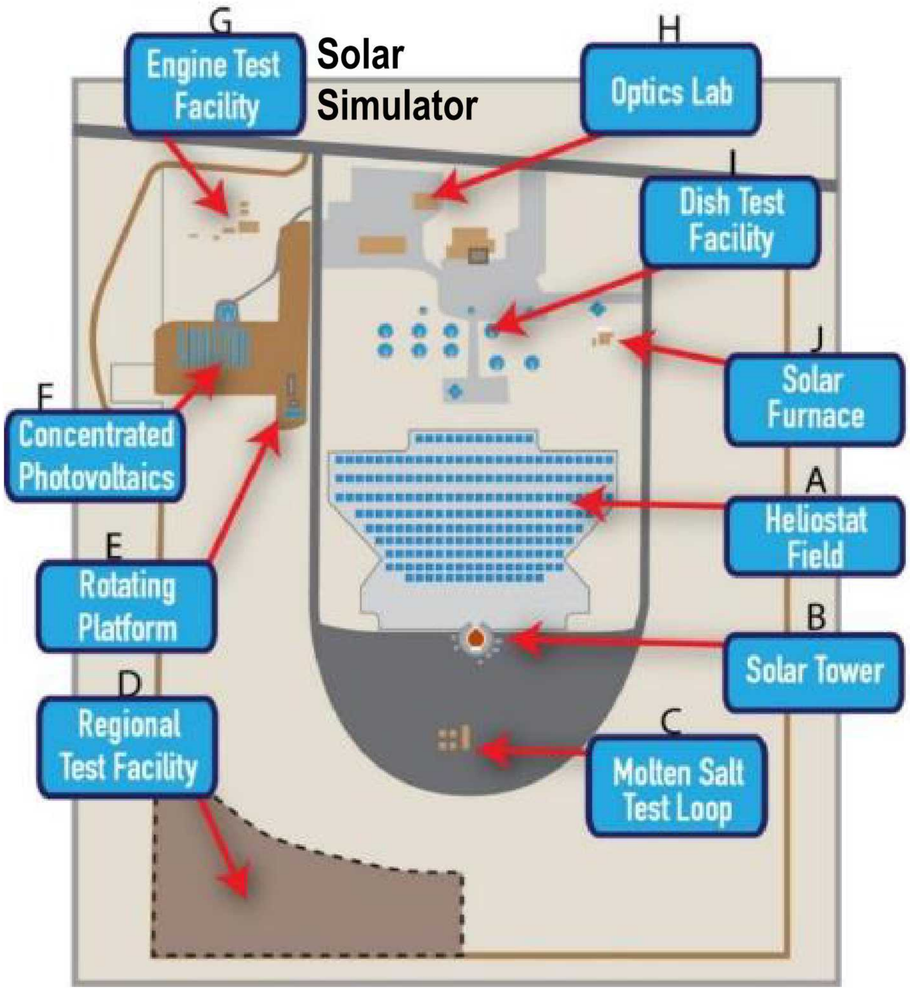
CSP and Thermal Energy Storage

- 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



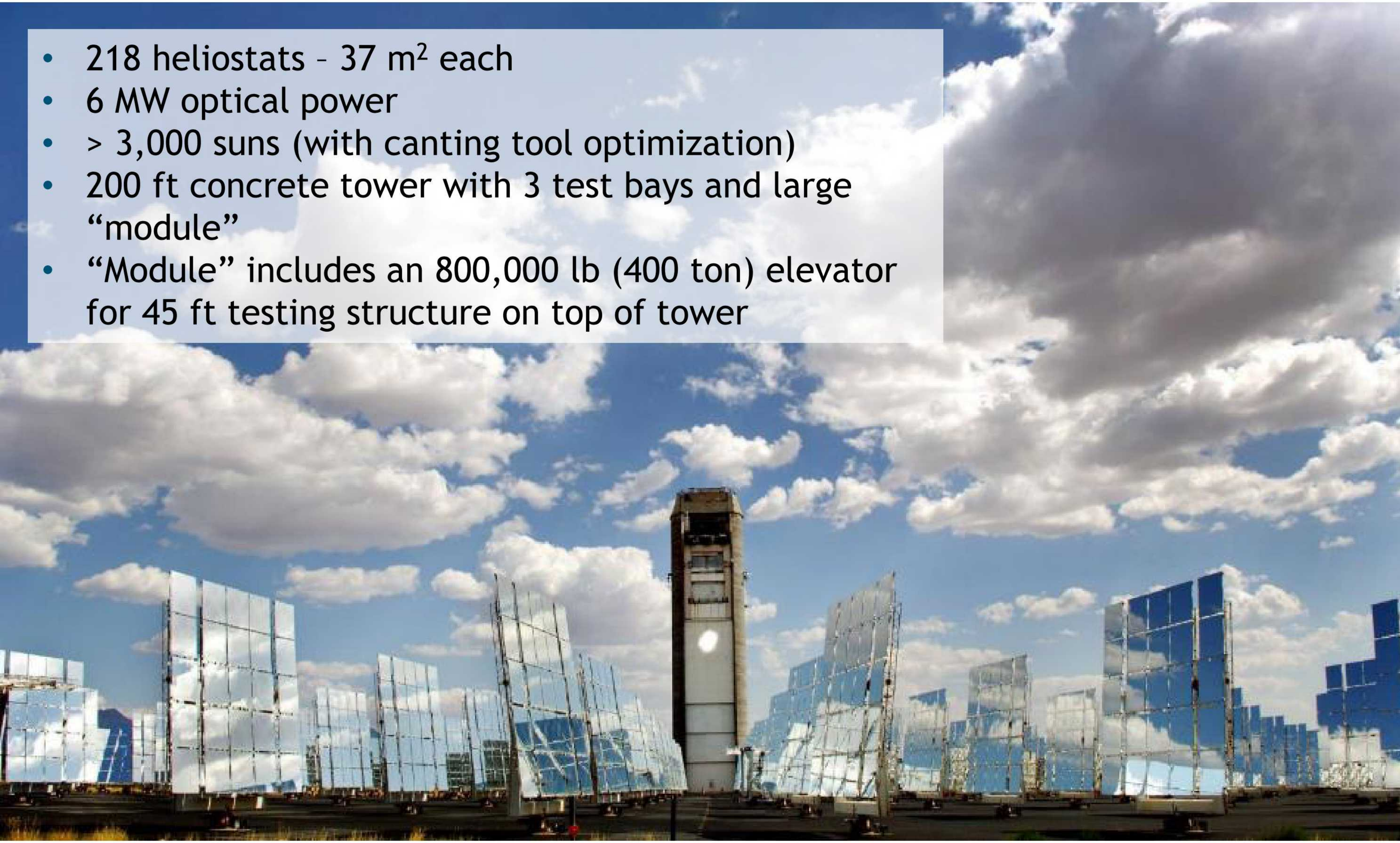
The National Solar Thermal Test Facility

NSTTF is a DOE Designated User Facility



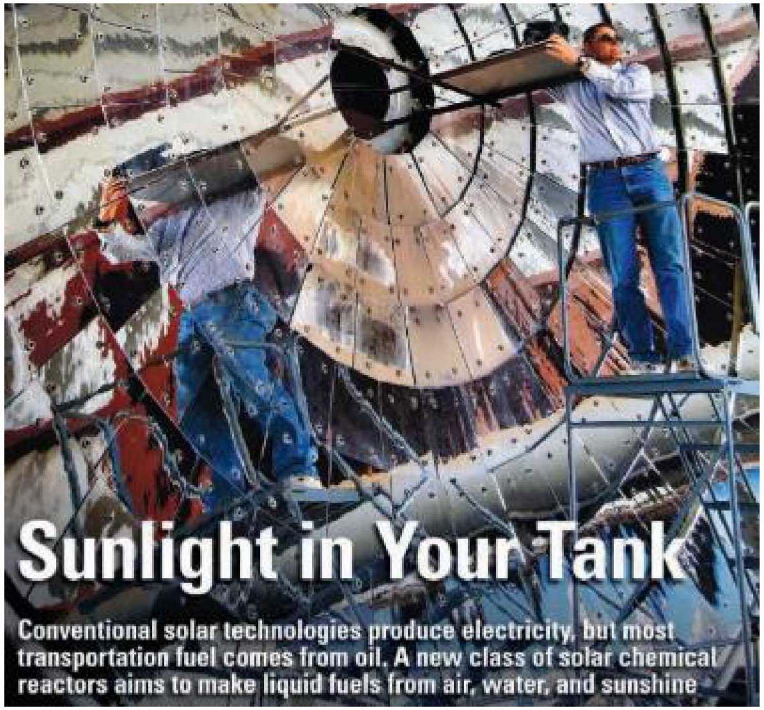
Solar Tower

- 218 heliostats – 37 m^2 each
- 6 MW optical power
- > 3,000 suns (with canting tool optimization)
- 200 ft concrete tower with 3 test bays and large “module”
- “Module” includes an 800,000 lb (400 ton) elevator for 45 ft testing structure on top of tower



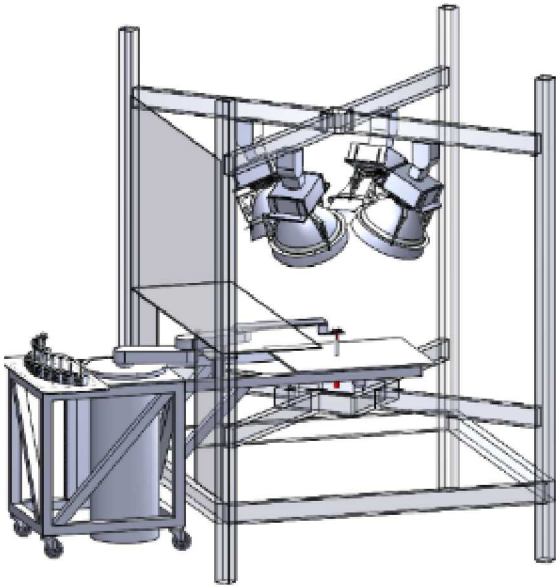
Solar Furnace

- 16 kW Solar Furnace
- Peak flux ~600 W/cm2 (6000 suns)
- 5 cm spot size



Solar Simulator

- High-Flux Solar Simulator with Automated Sample Handling and Exposure System (ASHES)
  - Four 1.8 kW lamps
    - $7.2\ kW_{electric}$, $6.2\ kW_{radiative}$
  - 1100 kW/m2 peak flux over 1 inch spot size



Materials in CSP

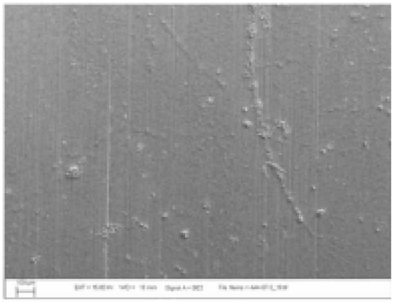
(or why you should be nice to your local materials chemist)

At its most basic, *"everything comes down to materials."*

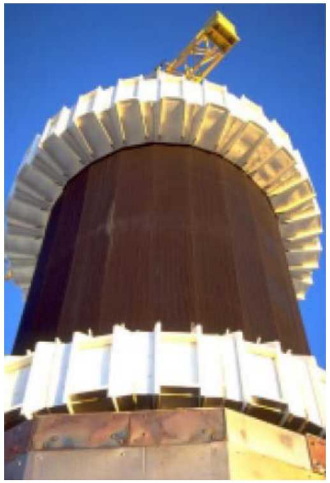
- Construction materials (alloys, ceramics, concrete)
- Coatings (absorptive, reflective, protective)
- Heat storage
- Corrosion
- Thermal conduction/expansion
- Heliostats
- Thermal stability
- Etcetera, etcetera, etcetera…

Ceramic particle storage

3M™ Solar Mirror Film 1100

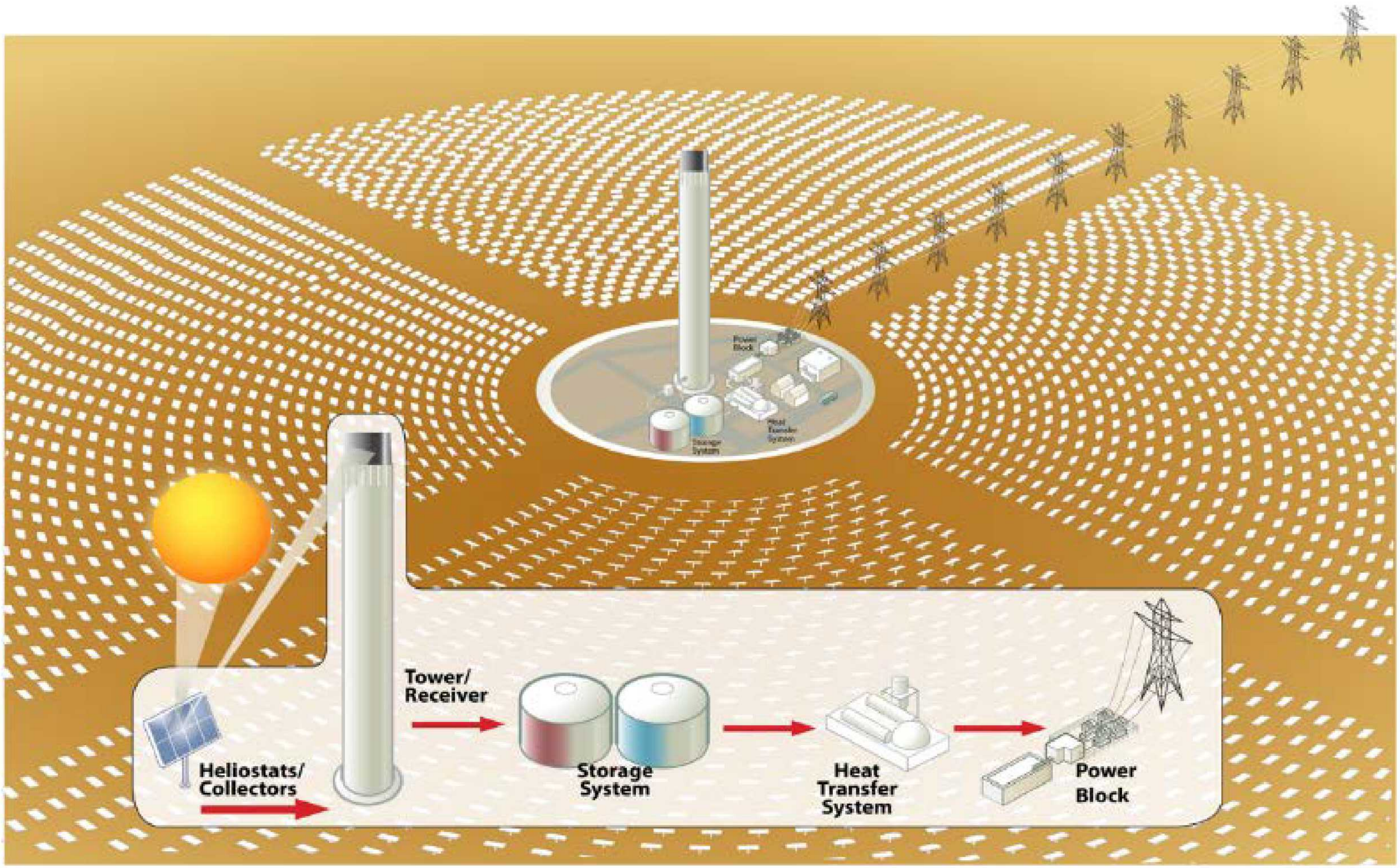


Left: $FeCo_2O_4$ coating
Right: SEM of $FeCo_2O_4$ surface (Scale bar = 100 μm)



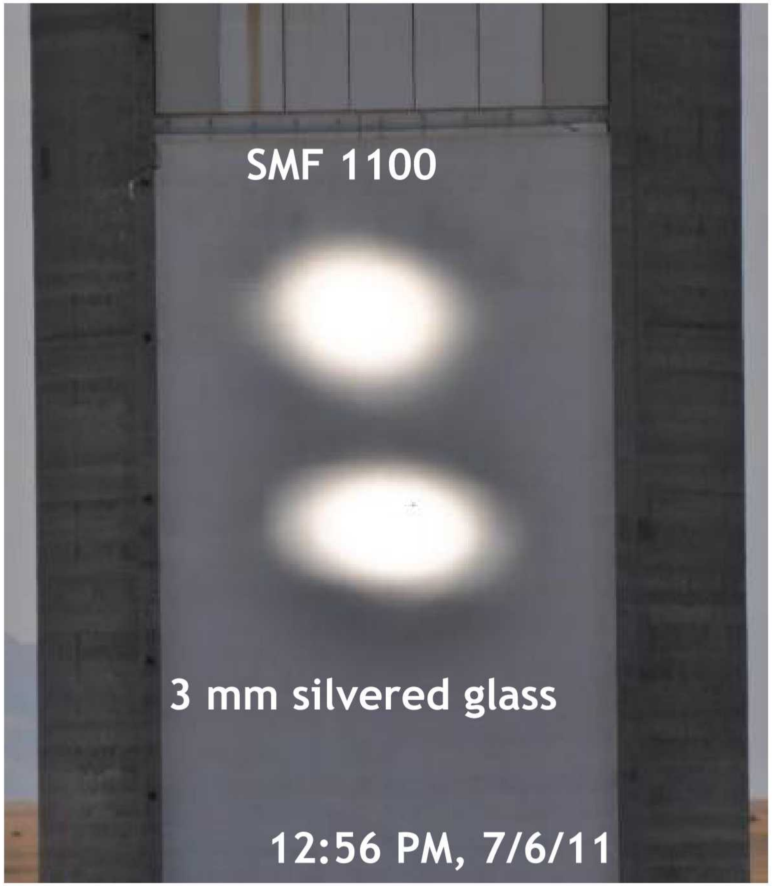
External tubular receiver

Sandia CSP Research



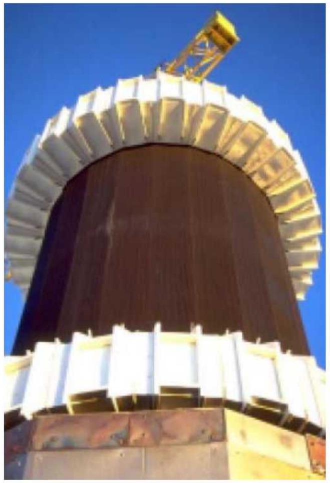
Advanced Reflective Materials

Heliostat with 3M™ Solar Mirror Film 1100



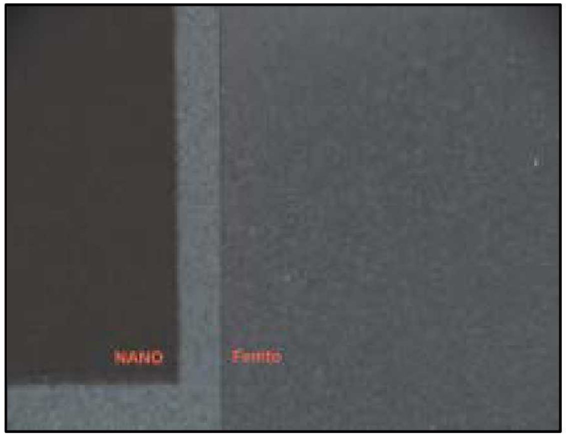
High-Temperature Receivers

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

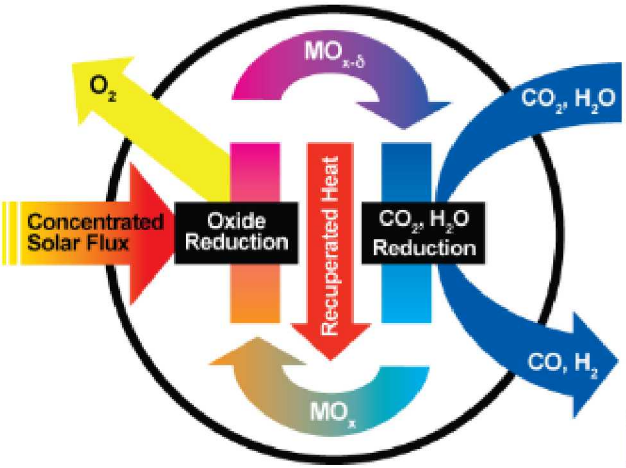


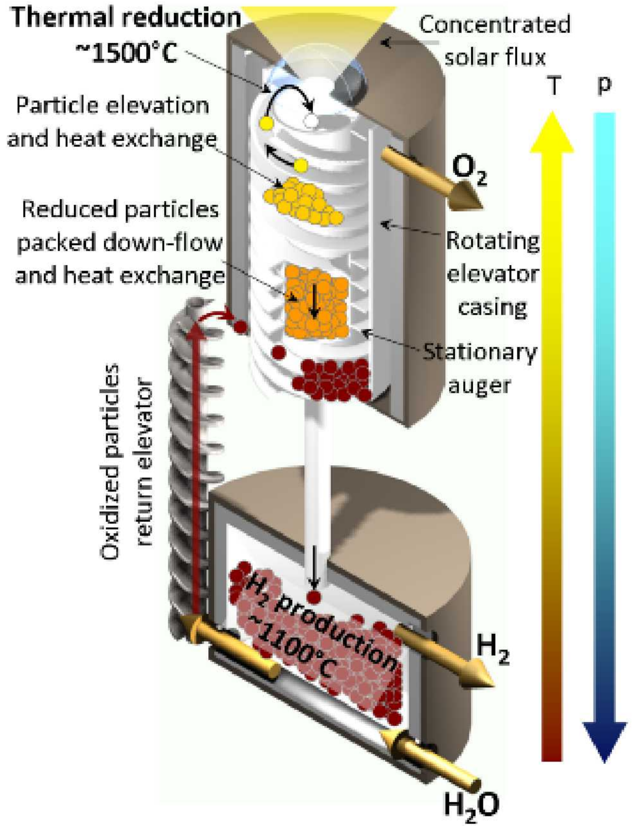
Solar absorptant coating

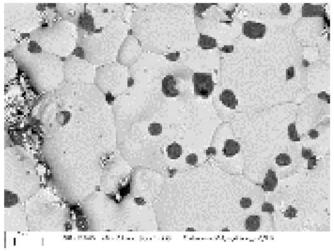
Solar Fuels

Creating hydrogen and liquid fuels with concentrated sunlight

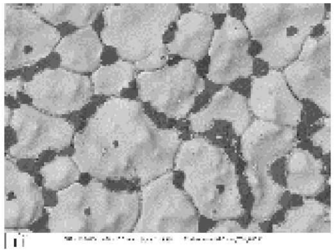
Sunlight + H_2O (+ CO_2) → H_2 (Fuel) + O_2



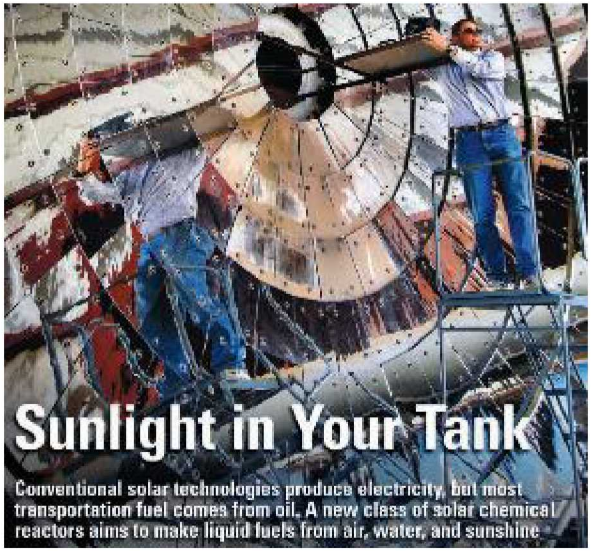




As-sintered



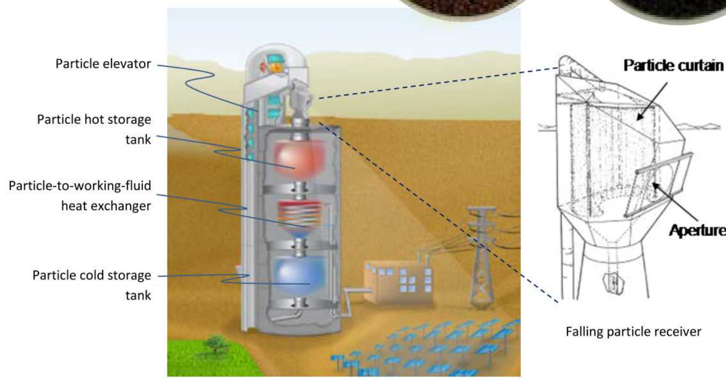
Post CO_2 TGA



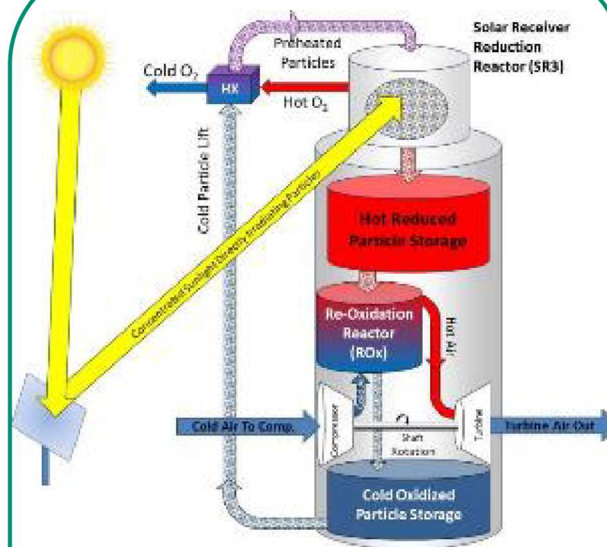
Ermanoski et al.

Sandia Research in Thermal Energy Storage

Corrosion studies in molten salt up to 700 C in "salt pots"

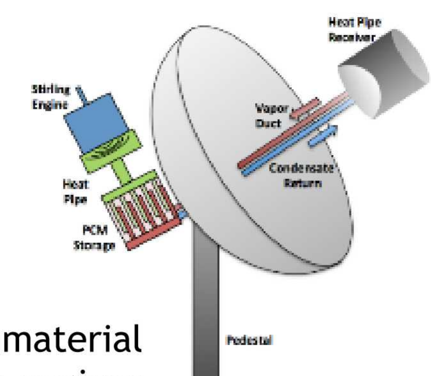


Ceramic particle storage and heating with falling particle receiver



Thermochemical particle storage with reduction/oxidation of perovskites

Component testing with molten-salt test



Latent phase-change material storage in dish engines

High Performance Reduction/Oxidation Metal Oxides for Thermochemical Energy Storage (PROMOTES)

Andrea Ambrosini, James Miller, Sean Babiniec, Peter Loutzenhiser, Ellen Stechel, Sheldon Jeter, Hany Al-Ansary

Seminar, 2 November 2018
New Mexico State University

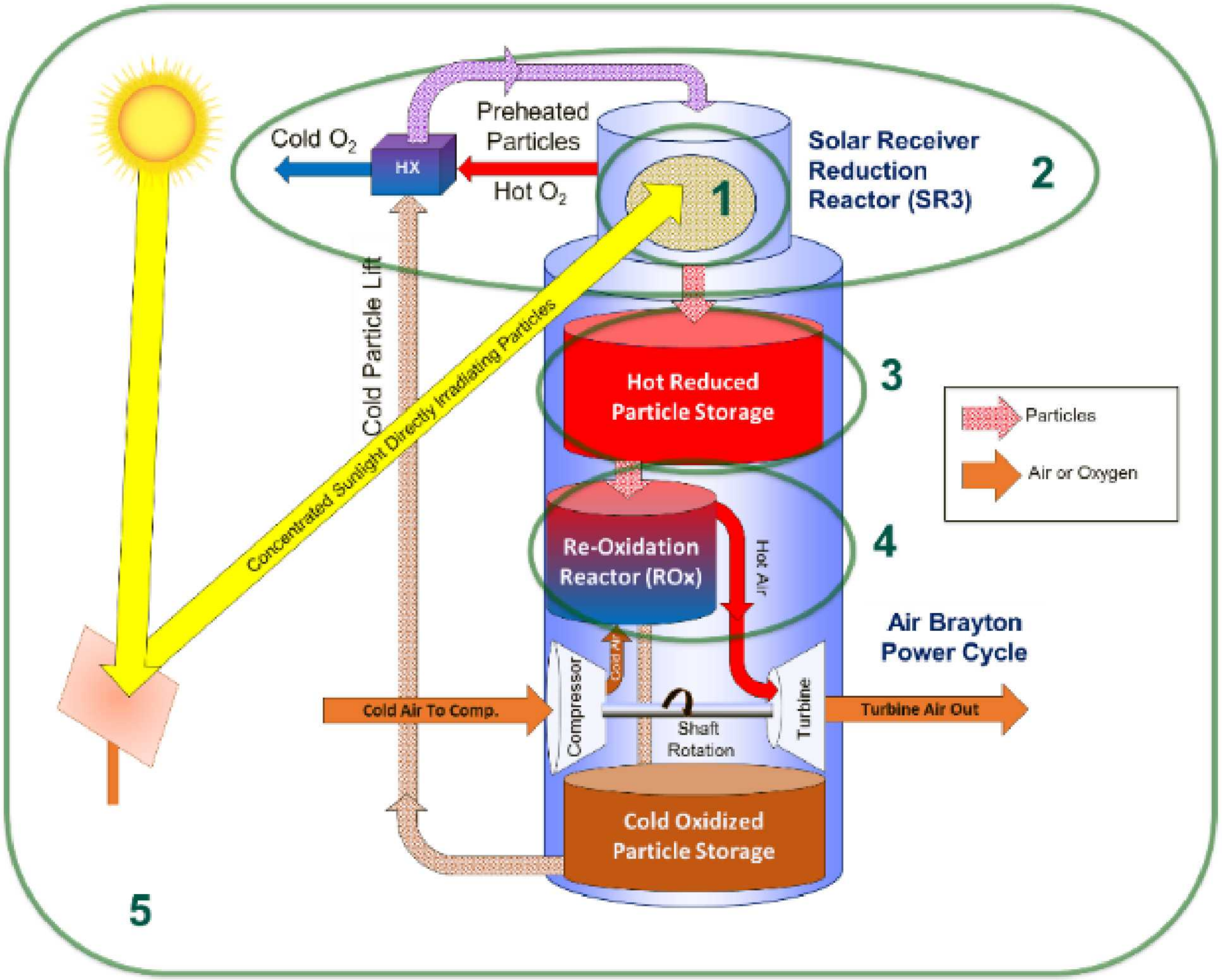
Thermochemical Energy Storage for CSP

- Next-generation (Gen3) CSP calls for operation at T > 700 ºC
- Current molten-salt storage systems are limited
  - Sensible-only storage, low storage densities
  - Salt decomposition limits turbine operating temperatures
- Thermochemical energy storage (TCES) offers many advantages
  - Ability store both sensible and redox reaction enthalpy, resulting in high storage densities:

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

  - Increased storage temperatures can enable the use of high-efficiency power cycles
    - Air Brayton inlet T ≥ 1200 °C
  - Direct irradiation of thermal storage media

High Performance Reduction/Oxidation Metal Oxides for Thermochemical Energy Storage



1. Materials Enabled Innovation ($\Delta H_{total} \geq 1500$ kJ/kg)

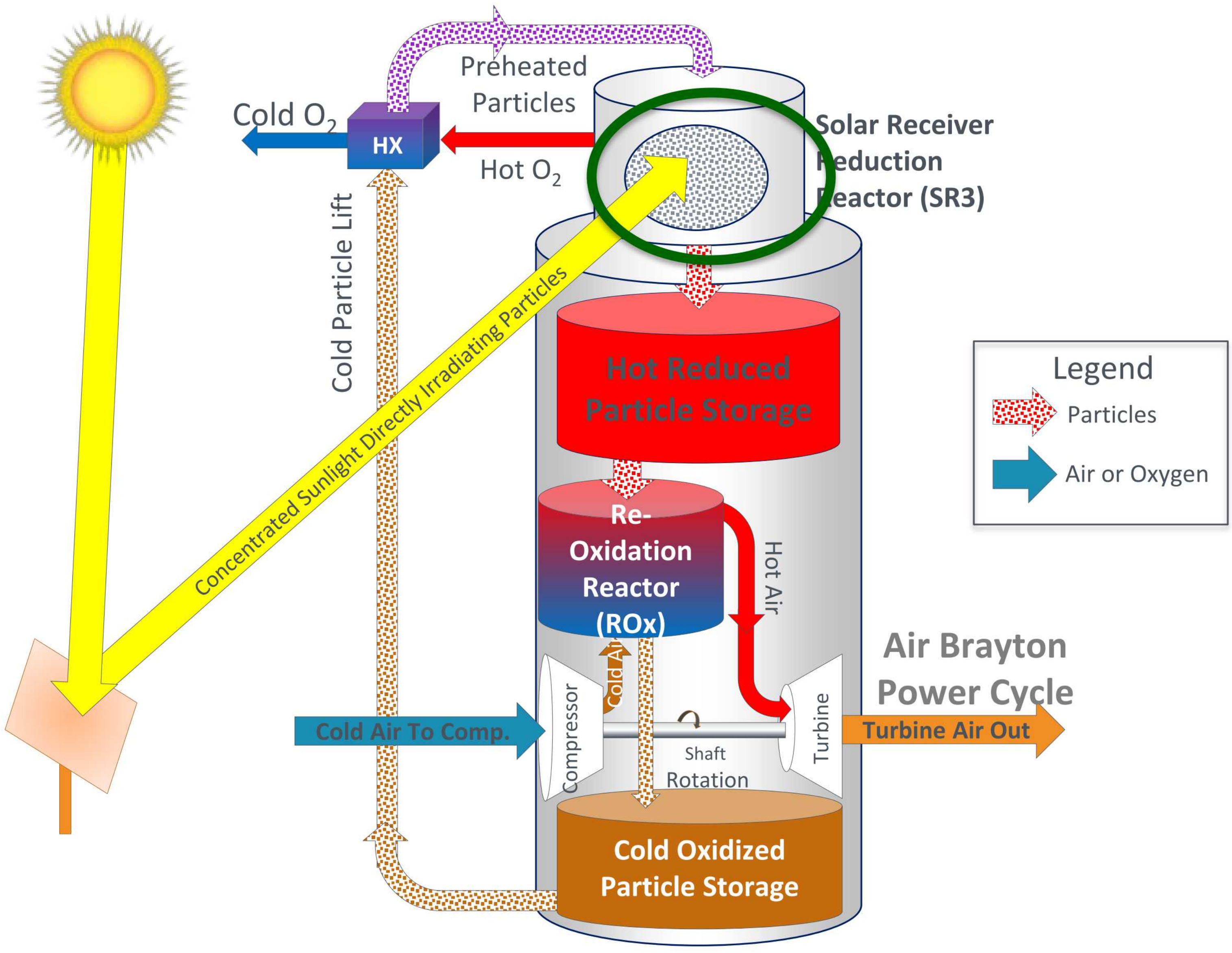
2. Solar Receiver Reduction Reactor

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. Systems and technoeconomics to predict cost and performance and to guide development efforts

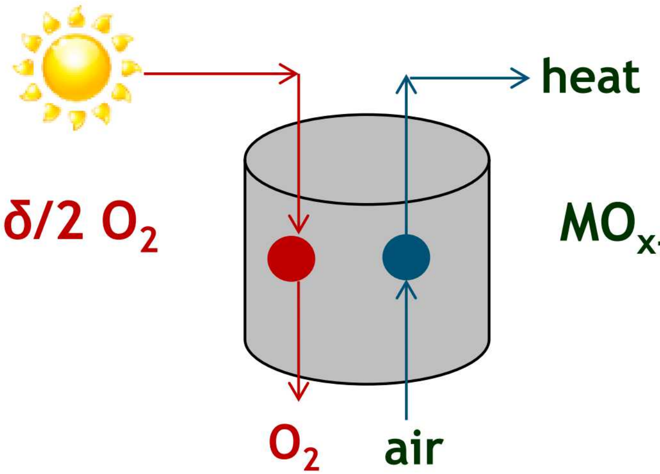
1. Materials


Preheated Particles
Cold O$_2$
HX
Hot O$_2$
Solar Receiver Reduction Reactor (SR3)
Cold Particle Lift
Concentrated Sunlight Directly Irradiating Particles
Hot Reduced Particle Storage
Re-Oxidation Reactor (ROx)
Hot Air
Cold Air
Compressor
Turbine
Shaft Rotation
Cold Air To Comp.
Air Brayton Power Cycle
Turbine Air Out
Cold Oxidized Particle Storage
Legend
Particles
Air or Oxygen

Metal Oxide TCES

Metal oxides are ideal materials for storage in high temperature cycles

$heat + MO_x \rightarrow MO_{x-\delta} + \delta/2\ O_2$



$MO_{x-\delta} + \delta/2\ O_2 \rightarrow heat + MO_x$

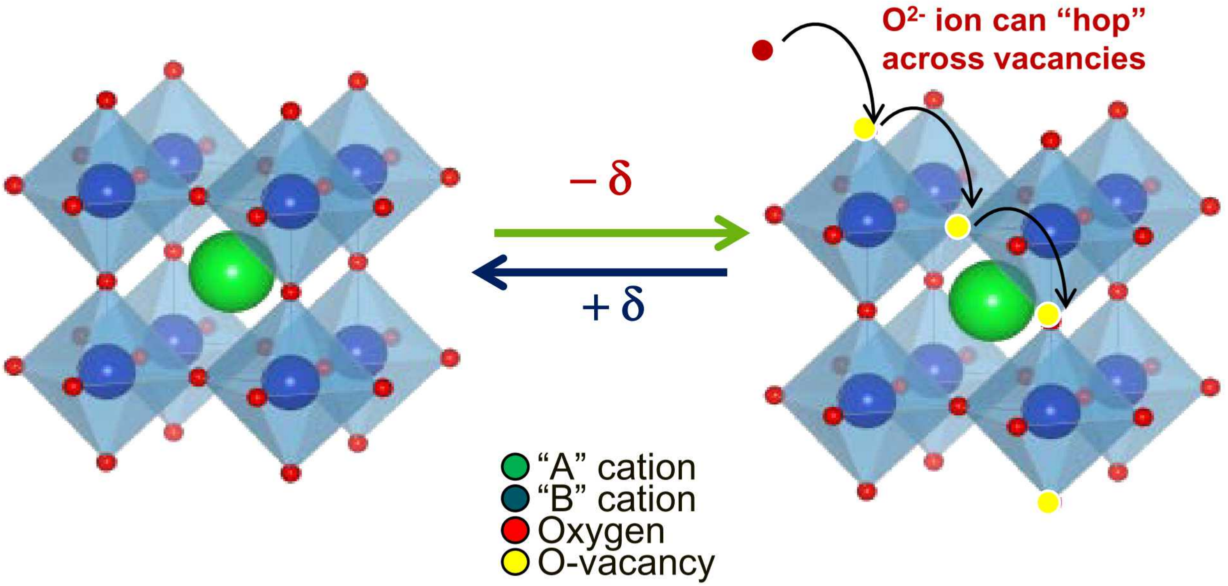
<u>Advantages of Metal Oxides (MO):</u>

- 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

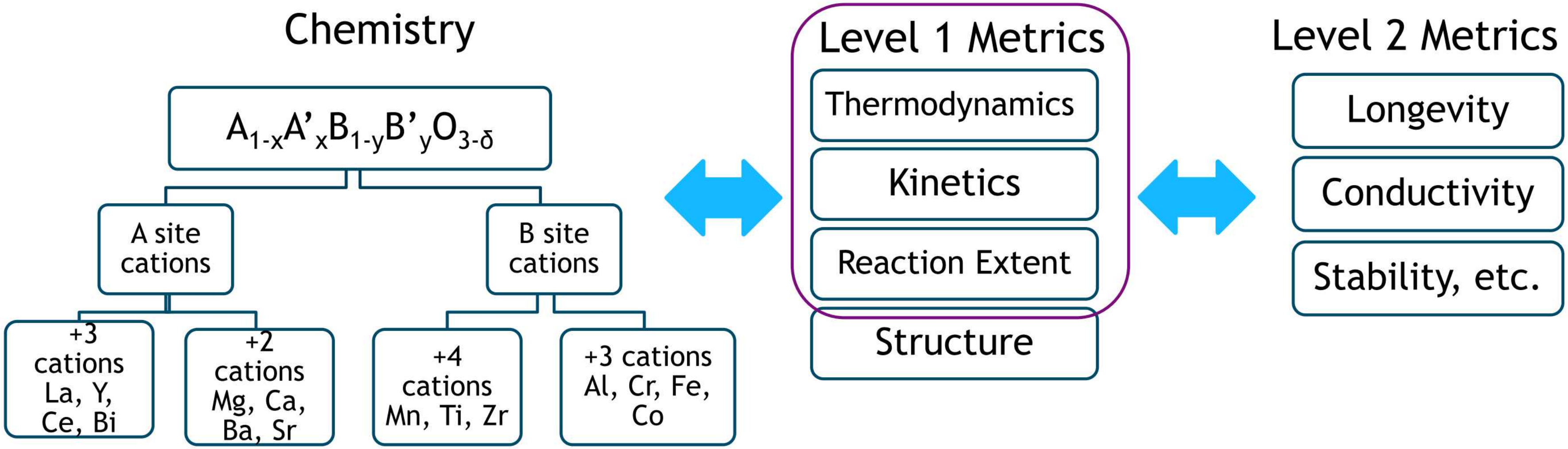
Mixed Ionic-Electronic Conducting (MIEC) Perovskites

$$ABO_3 \leftrightarrow ABO_{3-\delta} + \delta/2\ O_2(g)$$

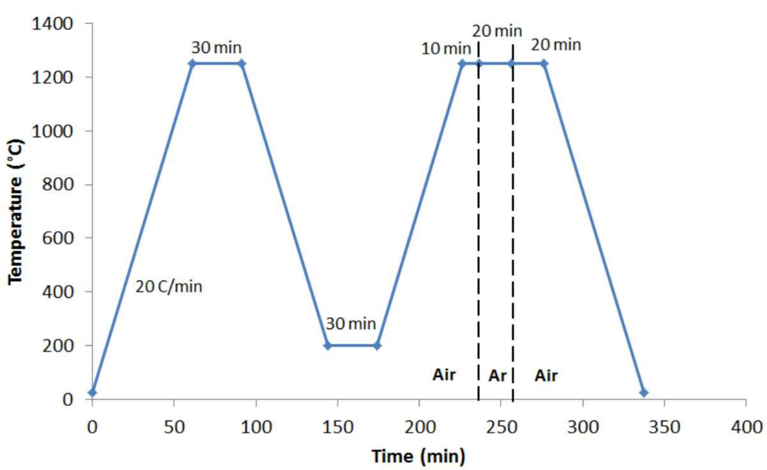
- No crystallographic phase change occurs during redox
- Vacancies facilitate oxide ion transport
- Electronic conductivity balances ionic conduction
- Redox activity continuous over variety of T and pO_2
- Can tune properties by doping on both A and B sites



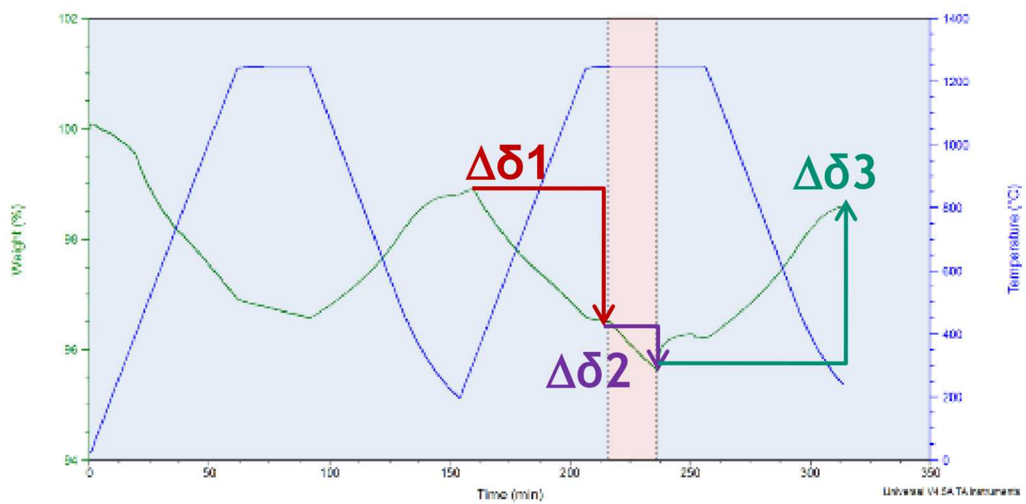
Systematic Approach and Metrics



Preliminary Screening – Thermogravimetric Analysis



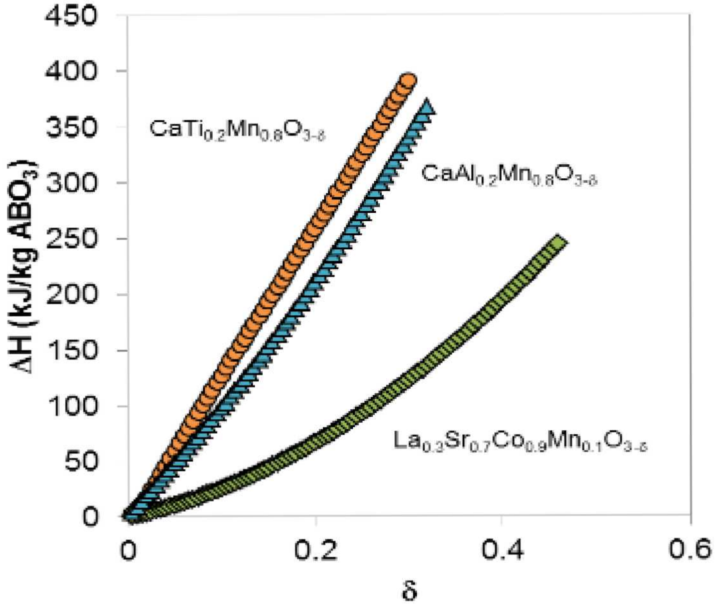
Pre-screen method

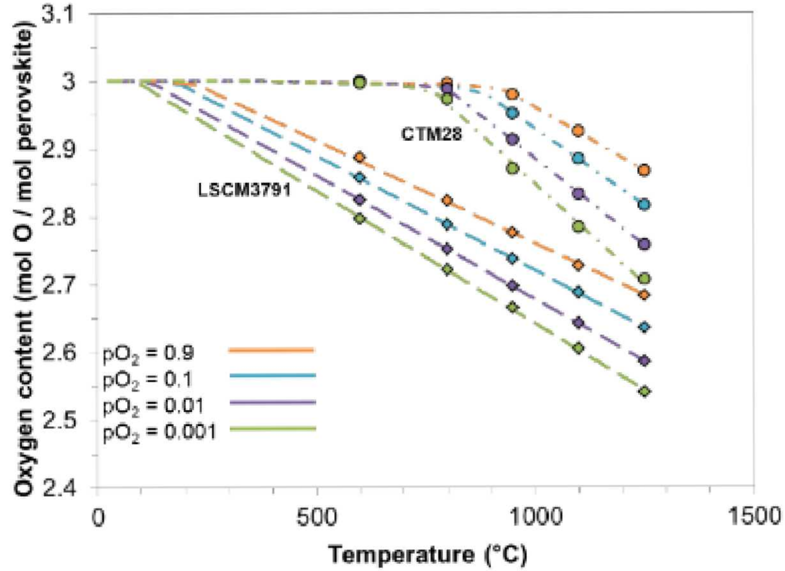


Example TGA

Reaction Enthalpy

$$ABO_3 + \Delta H_{rxn} \leftrightarrow ABO_{3-\delta} + \delta/2\ O_2(g)$$



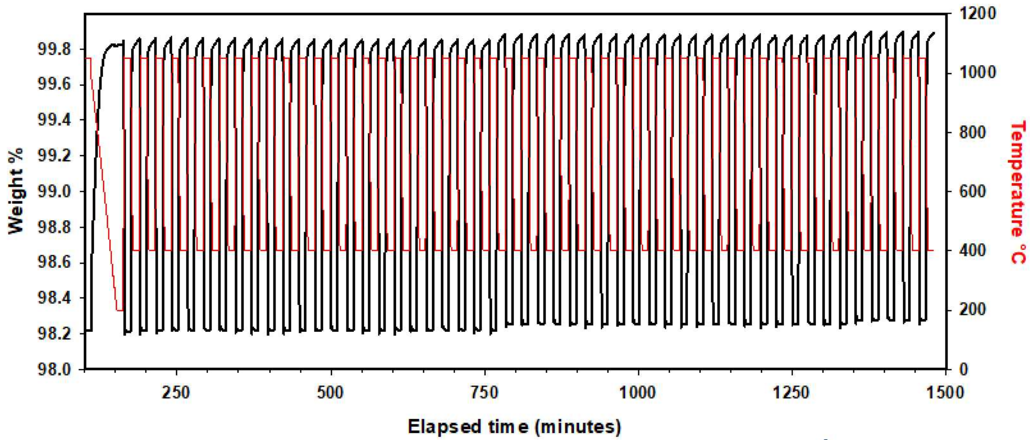


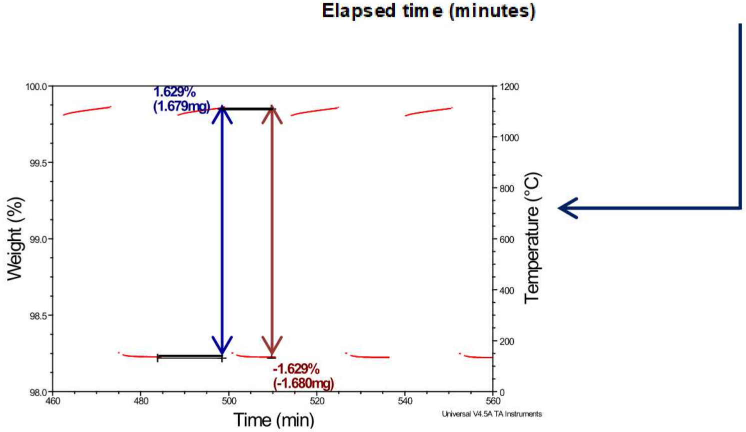
$$\Delta H_{tot} = \Delta H_{rxn} + C_p \Delta T$$

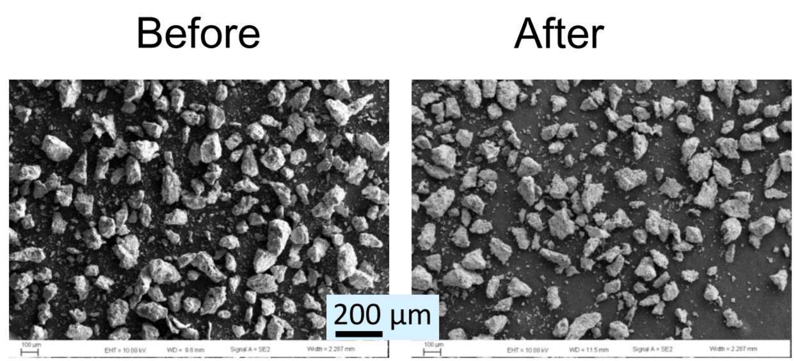
Candidate material	Mol weight (g/mol)	T_{red} Onset (°C)	Max δ	ΔH_{rxn} (kJ/kg) (at δ_{max})	C_p (kJ/kg-K)	ΔH_{tot} (kJ/kg)
LSCM3791	209.5	343	0.461	242	*0.595	837
CTM28	141.6	901	0.293	393	*0.881	1274
CAM28	135.8	759	0.322	371	*0.910	1281

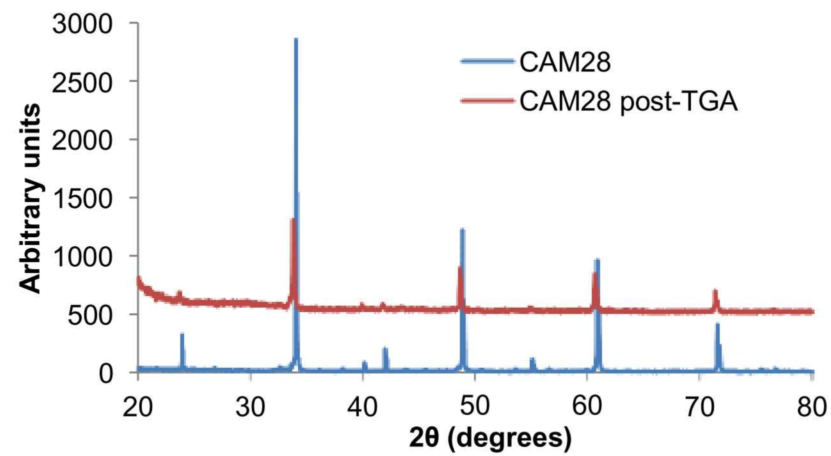
$CaAl_{0.2}Mn_{0.8}O_3$ (CAM28) Cyclic Behavior

- Multi-cycle TGA used to measure cyclic repeatability and stability
  - Particles heated to 1000 °C, cooled to 400 °C for 100 cycles
- Scanning electron microscopy shows no change in morphology
- XRD shows no change in crystal phase

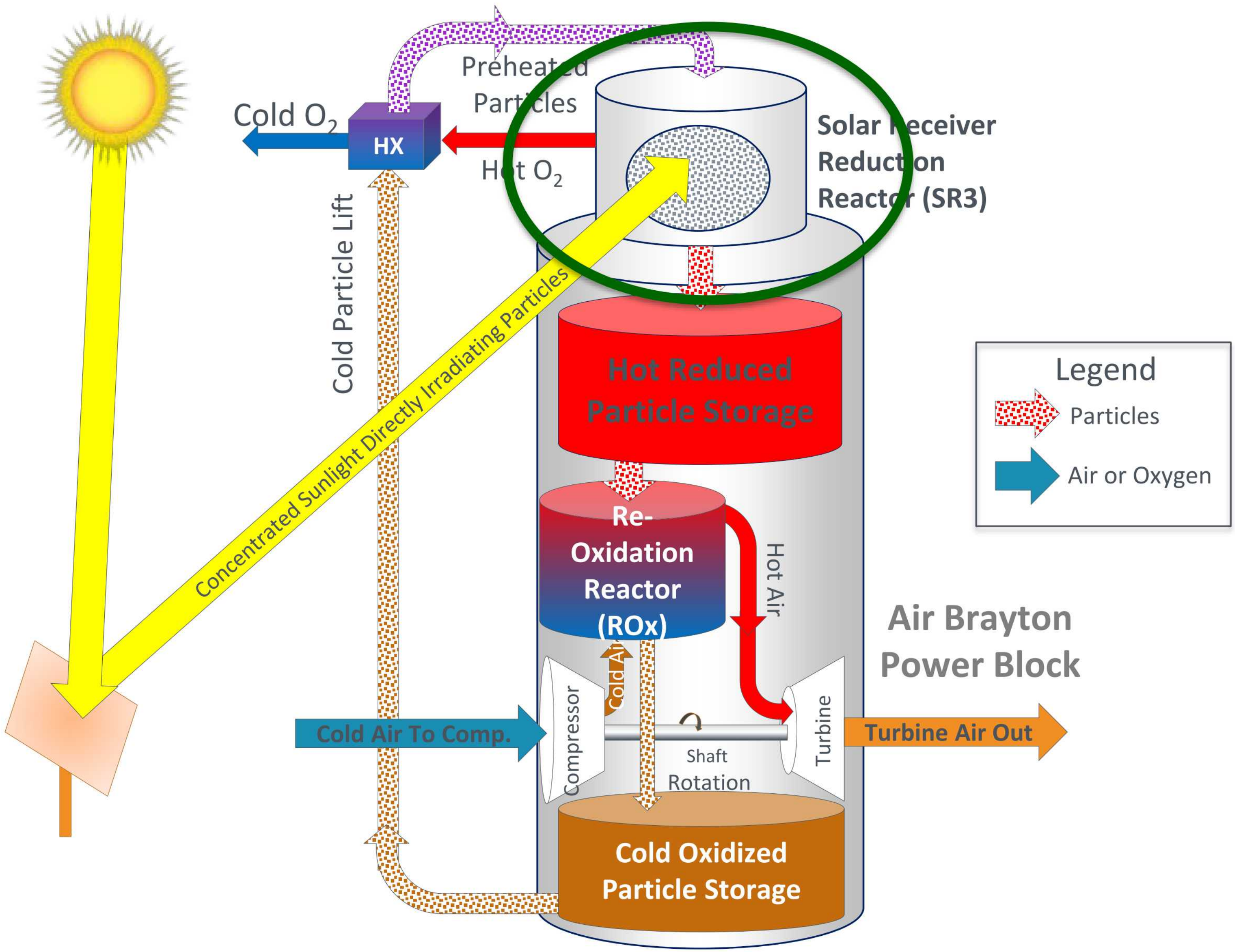








2. Solar Receiver Reduction Reactor (SR3)



Solar Thermochemical Inclined Granular-Flow Reactor (STINGR)

- 5 kWth scale reactor designed, manufactured, tested in the Solar Fuels and Technologies Laboratory at Georgia Tech using a Xe arc-lamp high flux solar simulator
- Reactor goals:
  - Direct irradiation of energy storage media
  - Continuous, on-sun operation
  - Matched incident concentrated solar power to rate of energy storage
- Reactor goals achieved using directly irradiated, thin, dense granular flows of reactive CAM28 particles
- Reactor operated at reduced pressure using quartz-glass window, promote CAM28 reduction

Solar Fuels and Technologies Laboratory High Flux Solar Simulator at Georgia Tech

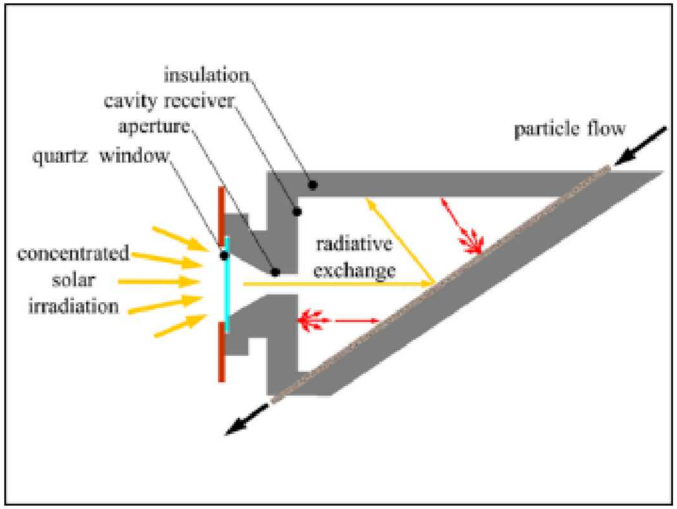
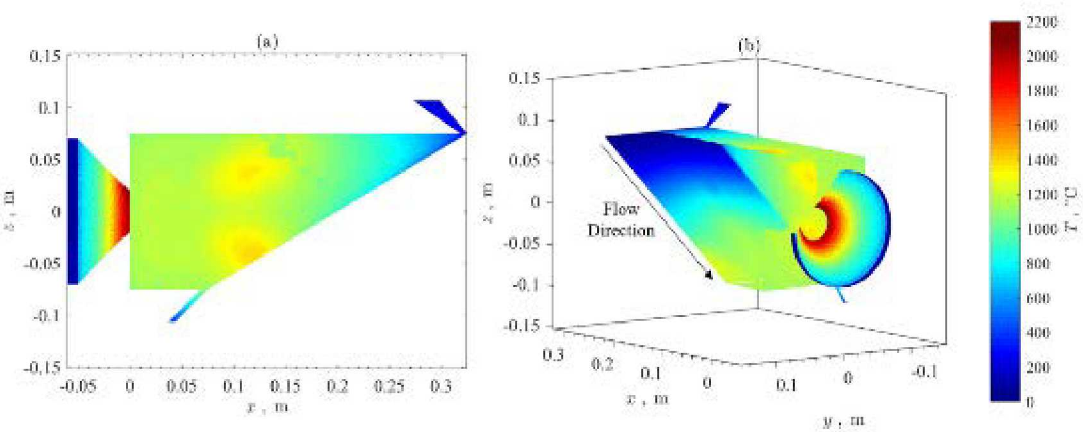


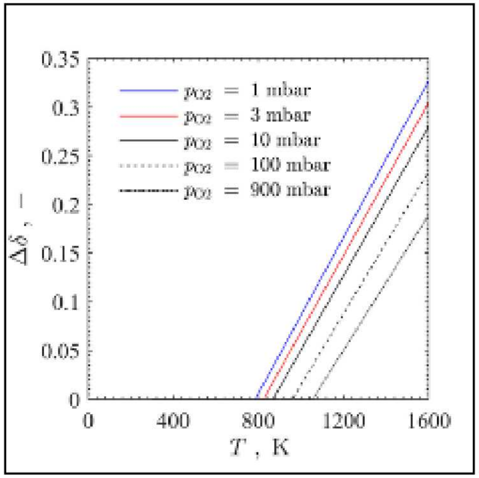
Diagram of solar thermochemical inclined granular-flow reactor

STINGR Heat and Mass Transfer Modeling

- Combined heat and mass transfer model developed to gain further insight into performance of STINGR
  - Energy storage, transport of dense granular flow of CAM28 particles
  - Radiative exchange, absorption incident radiation from HFSS in reactive dense, granular flow
- Coupled, radiation models
  - Directional, radiative input – Monte Carlo Ray Tracing
  - Inter-cavity radiative exchange – Discretized radiative transport equation
  - Optically thick dense, granular particle flow – Rosseland diffusion approximation
- CAM28 reduction assumed thermodynamically limited, characterized from prior Van't Hoff equilibrium analysist

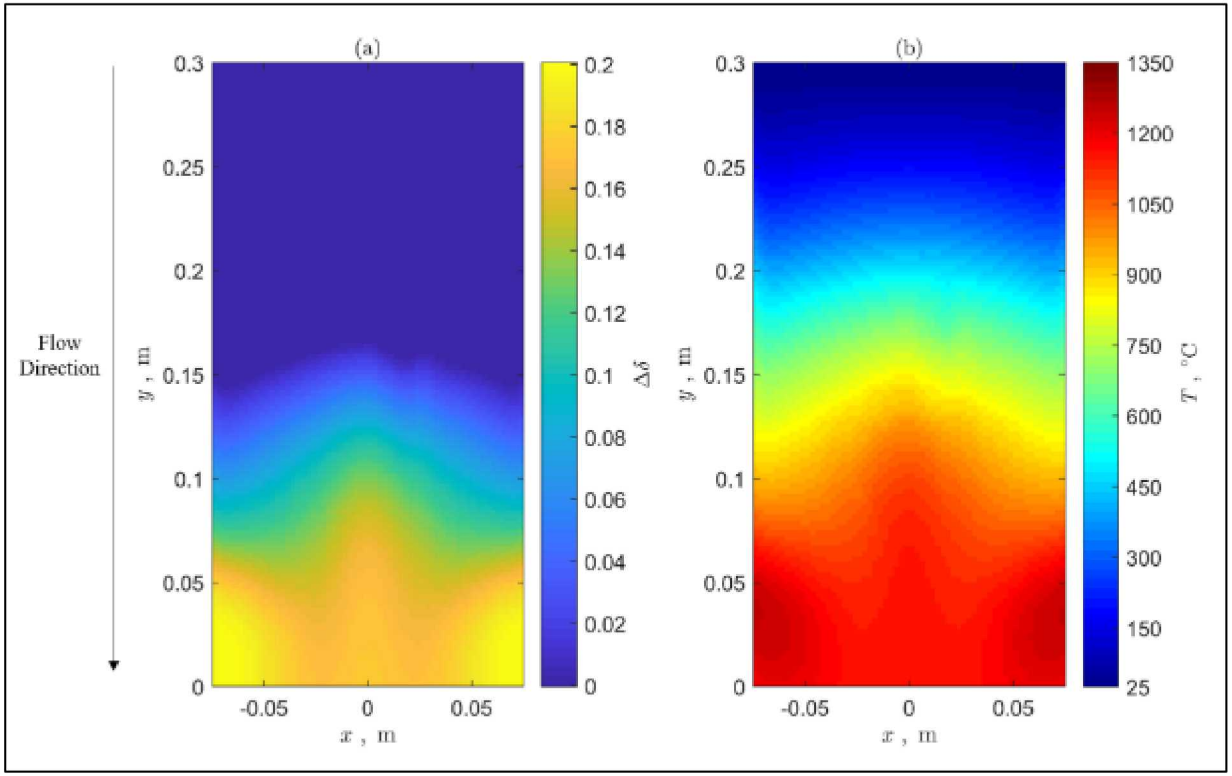


Temperature contours for steady-state model as viewed from the side (left) and above (right)



Fitted response surface for CAM28 stoichiometric deviation as a function of T and pO_2

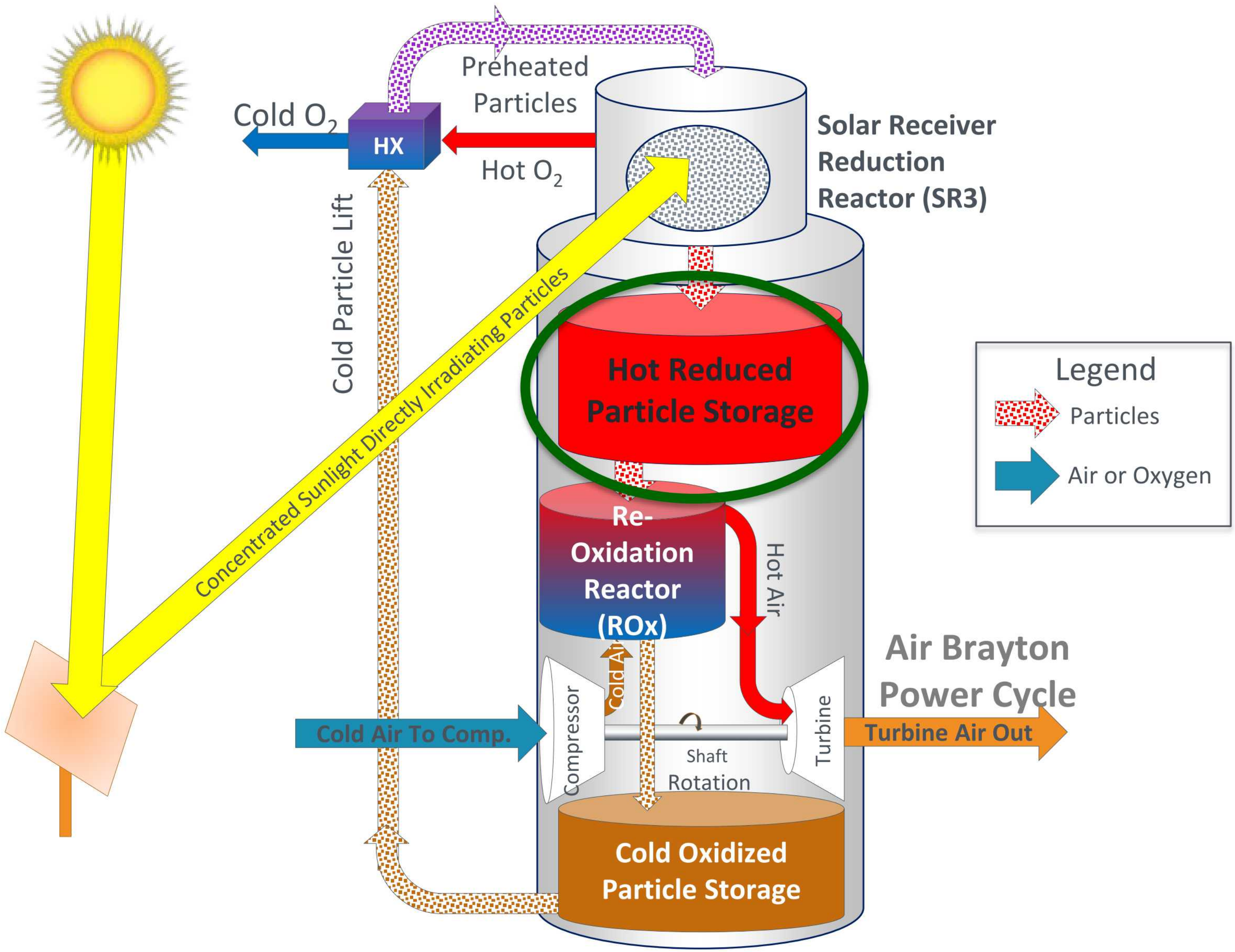
STINGR Heat and Mass Transfer Modeling – Steady State



Contours of CAM28 deviation from stoichiometry (left) and CAM28 temperature (right) for dense, granular particle flow within the solar thermochemical inclined granular-flow reactor

Performance Parameters	Value
$\bar{T}_{\text{particle,outlet}}$	1173.6 ˚C
$\Delta\delta_{\text{outlet}}$	0.183
η	0.701

3. Hot Particle Storage

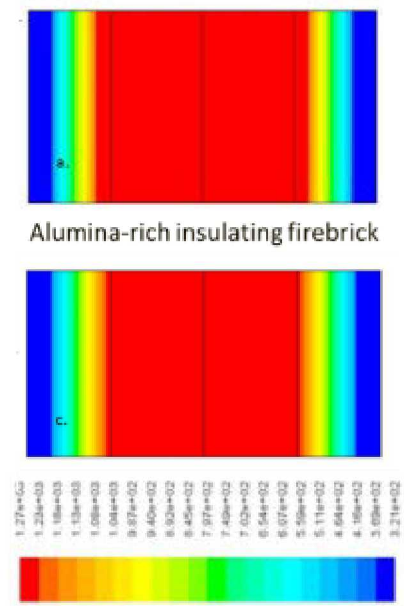


Hot Particle Storage

Design, cost, & thermal analysis of inert atmosphere hot particle storage bin

	Internal bin temperature	
	1000°C	1350°C
Temperature range in IFB (°C)	817-1000	1100-1350
Temperature range in PC (°C)	162-817	209-1100
Temperature range in EB (°C)	63-162	74-209
Temperature range in RC (°C)	45-63	51-74
Rate of heat loss (kW)	111	152
Heat loss to nitrogen (GJ)	2.0	2.7
Total energy loss over storage period (GJ)	5.2	4.4
Percentage loss of energy content	0.12%	0.18%

Bin wall construction



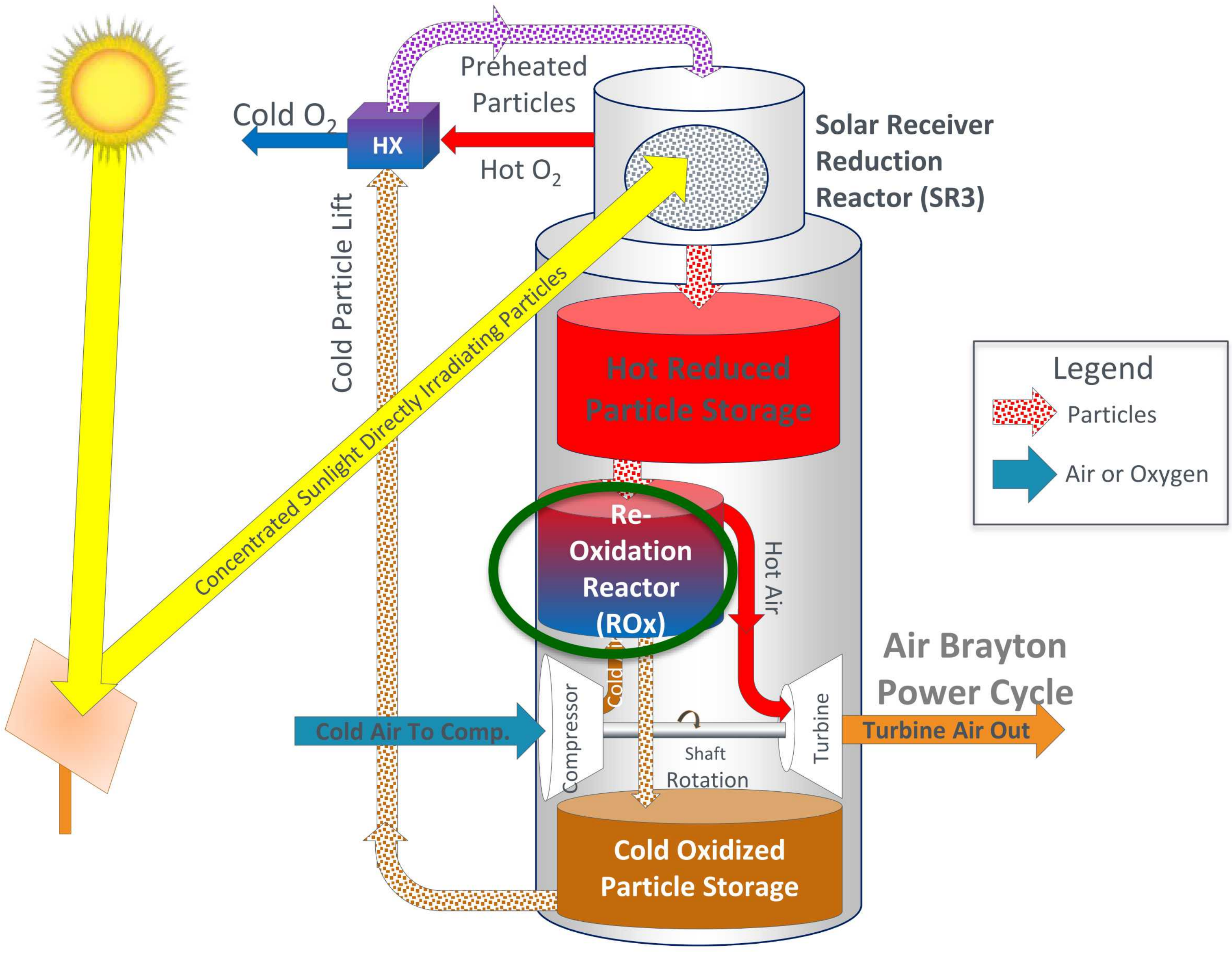
Chemical compatibility of insulating materials with MIECs: Zr-rich liners offer improved chemical resistance with thermal performance similar to conventional alumina firebrick

	SRI HF-IB 1260	ZIRMUL	Zirnorite 699	Zirnorite 192	Silicon Carbide
Fe_2O_3	R	R	NR	NR	NR
$La_{0.8}Sr_{0.2}CoO_3$	R	R	NR	NR	NR
$SrFe_{0.5}Co_{0.5}O_x$	R	R	I	I	I
CaO	R	-	-	NR	NR
MgO	R	-	-	NR	I
$CaAl_{0.2}Mn_{0.8}O_3$	R	-	-	NR	NR
$CaTi_{0.2}Mn_{0.8}O_3$	R	-	-	NR	NR

R = Reactive; NR = Non-reactive; I = Inconclusive; - = Not tested

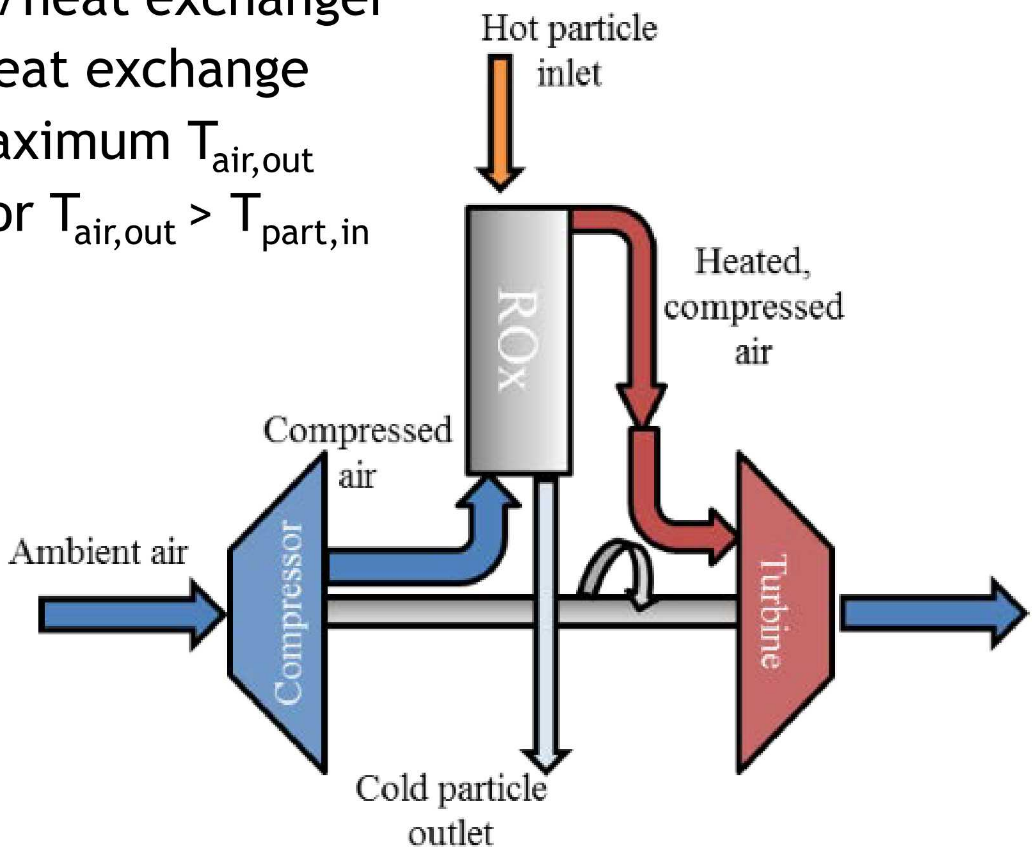
Characterizing oxidation resistance of duct materials

4. ReOxidation Reactor (ROx)



Reoxidation Reactor (Rox) Operational Concept

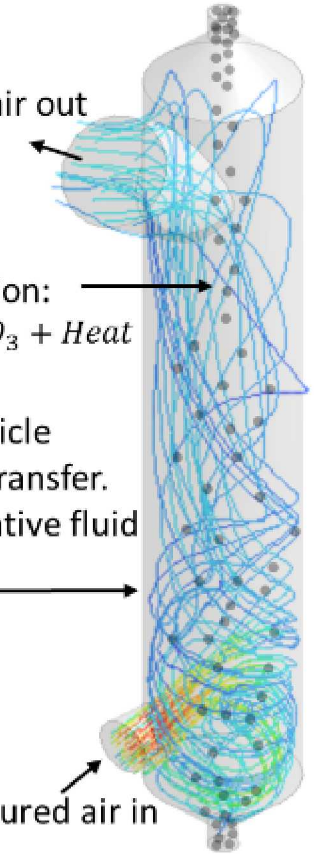
- ROx integrated into Air Brayton cycle
  - Replaces traditional combustor
- Air is working fluid and reactant stream (O_2)
  - Functions as a coupled reactor/heat exchanger
  - Direct-contact particle/fluid heat exchange
    - Counterflow operation for maximum $T_{air,out}$
    - Exothermic reaction allows for $T_{air,out} > T_{part,in}$
- Operating conditions
  - Pressure = 5-20 atm
  - Fluid inlet 300-400 °C
    - Isentropic compression
  - Particle inlet 1050-1150 °C
  - Fluid Tout ≥ 1200 °C



ROx Design and Modeling

Gravity-driven flow in vertical configuration appears most effective

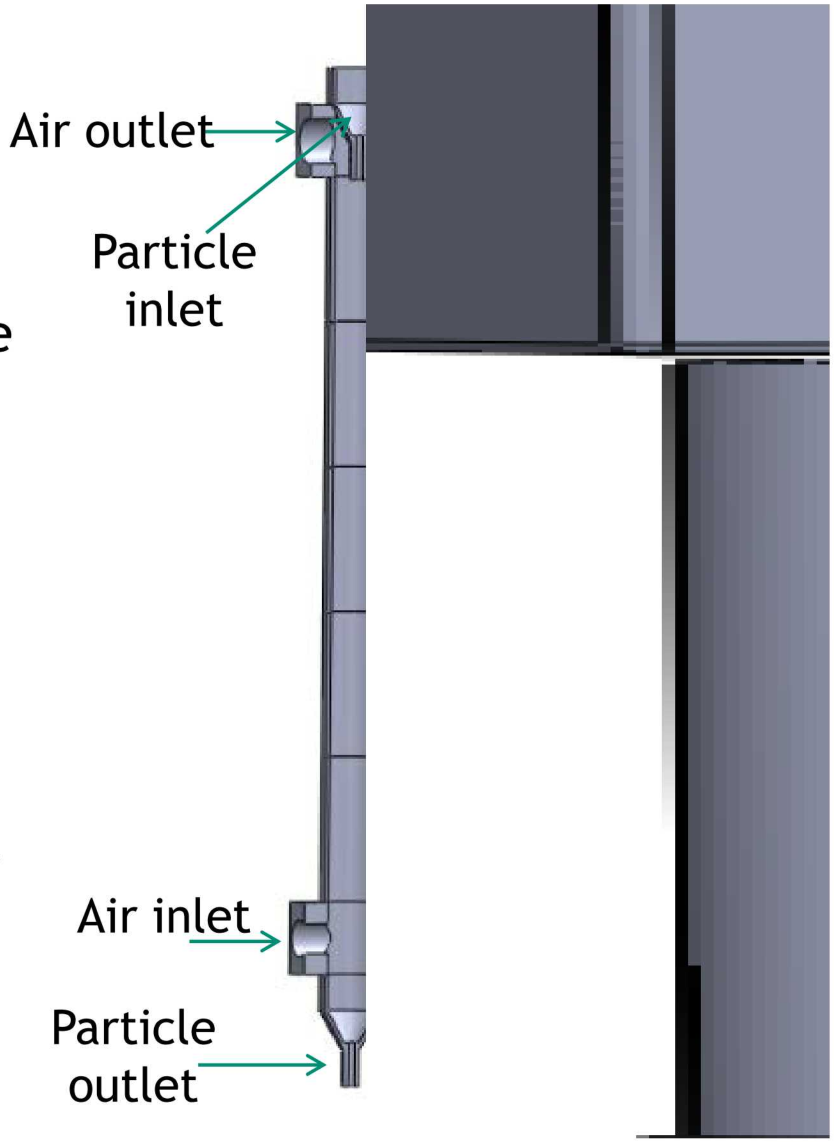
- Counter-flow falling-particle design
- Flow pattern optimizes heat transfer and reaction kinetics
- Low pressure drop due to dispersed particles
- 3-D geometry developed based on constraints identified in the 1-D model and entrainment calculations
- Variations of this geometry analyzed using 3-D Fluent model
  - Outlet tube diameter and main tube diameter studied

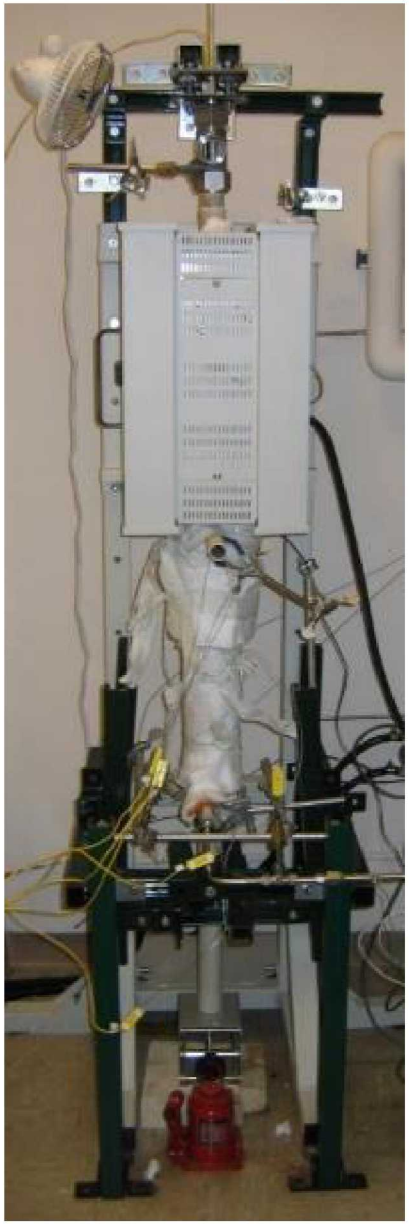


Bench-scale 1 kW ROx Reactor

Instrumentation:

- 1200 °C vertical tube furnace
- 1 particle reduction tube T/C
- 1 particle out T/C
- 3 fluid out T/C
- 1 “probe” T/C – insulation and exterior reactor wall
- Gas preheat up to 350°C with T/C and control circuit
- DAQ unit for T/C data collection



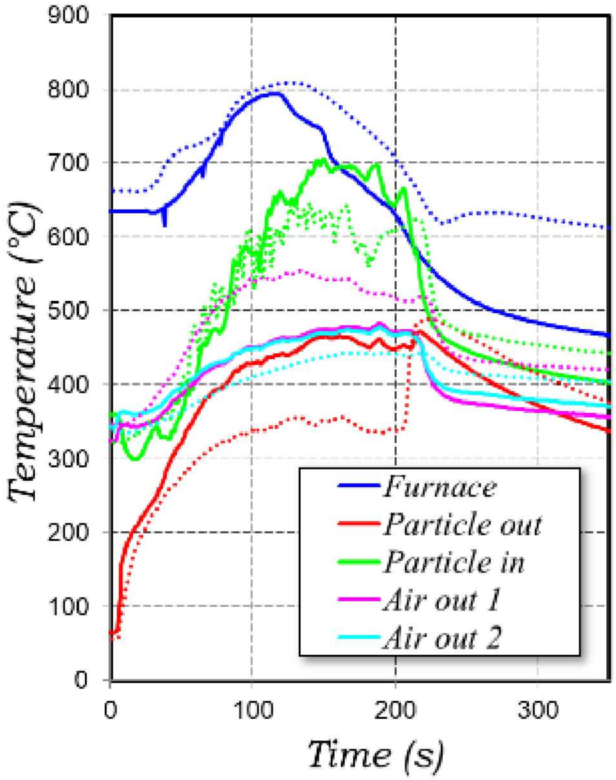


Segmented reactor allows thermal expansion, ability to add/remove segments

Reactive particle testing

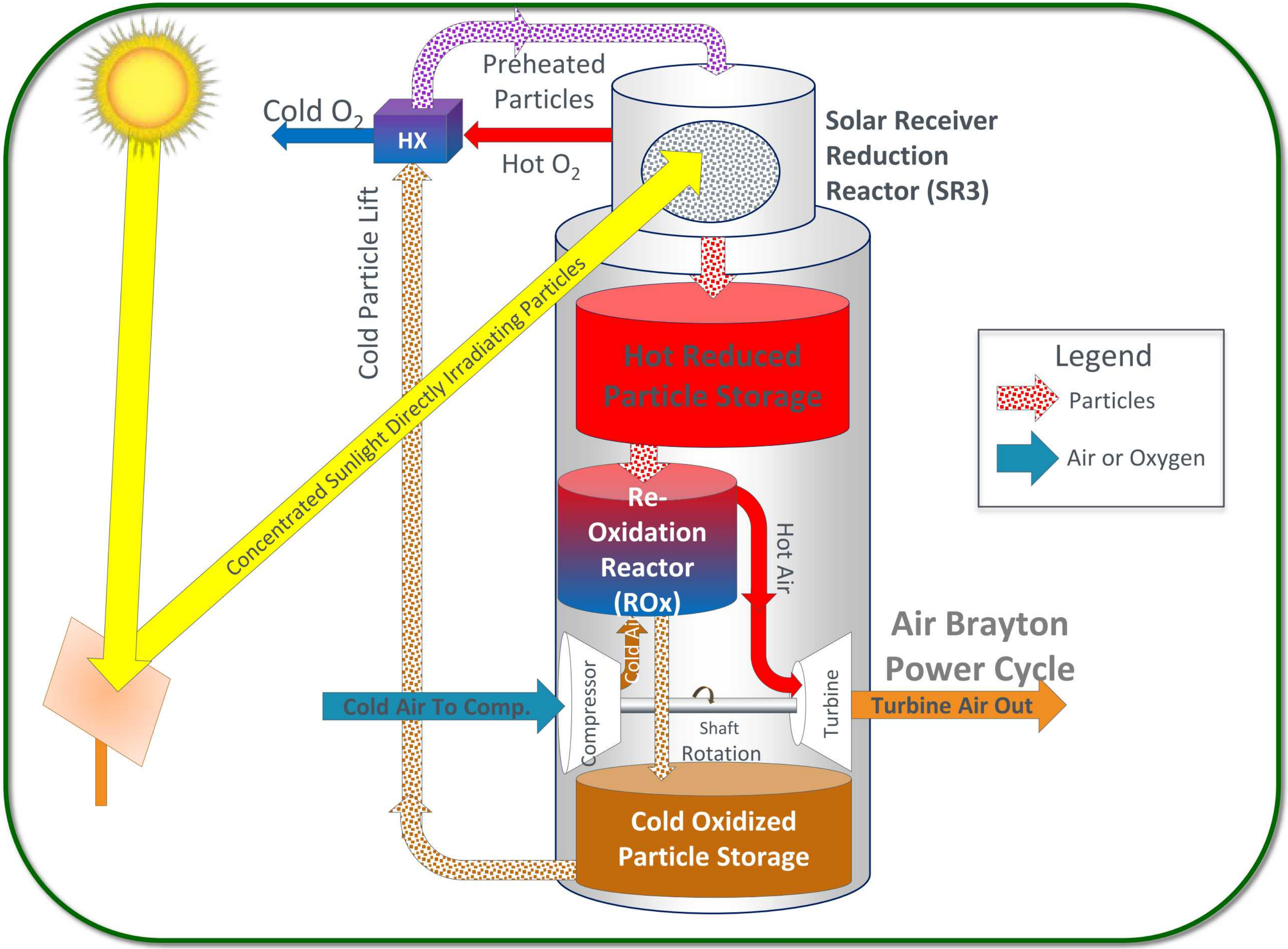
Reactive testing was performed using the $Ca_{1-x}Sr_xMnO_{3-\delta}$ (CSM) material provided by Colorado School of Mines

- Model thermodynamics updated with published literature
- Flowability of the particles suffered at T > 800 °C
  - 1000 °C runs exhibited clogging due to particle sintering
    - Attempted 3 runs, none were successful
  - Only 800 °C data was useful for model validation/calibration
    - Two runs completed with improved repeatability

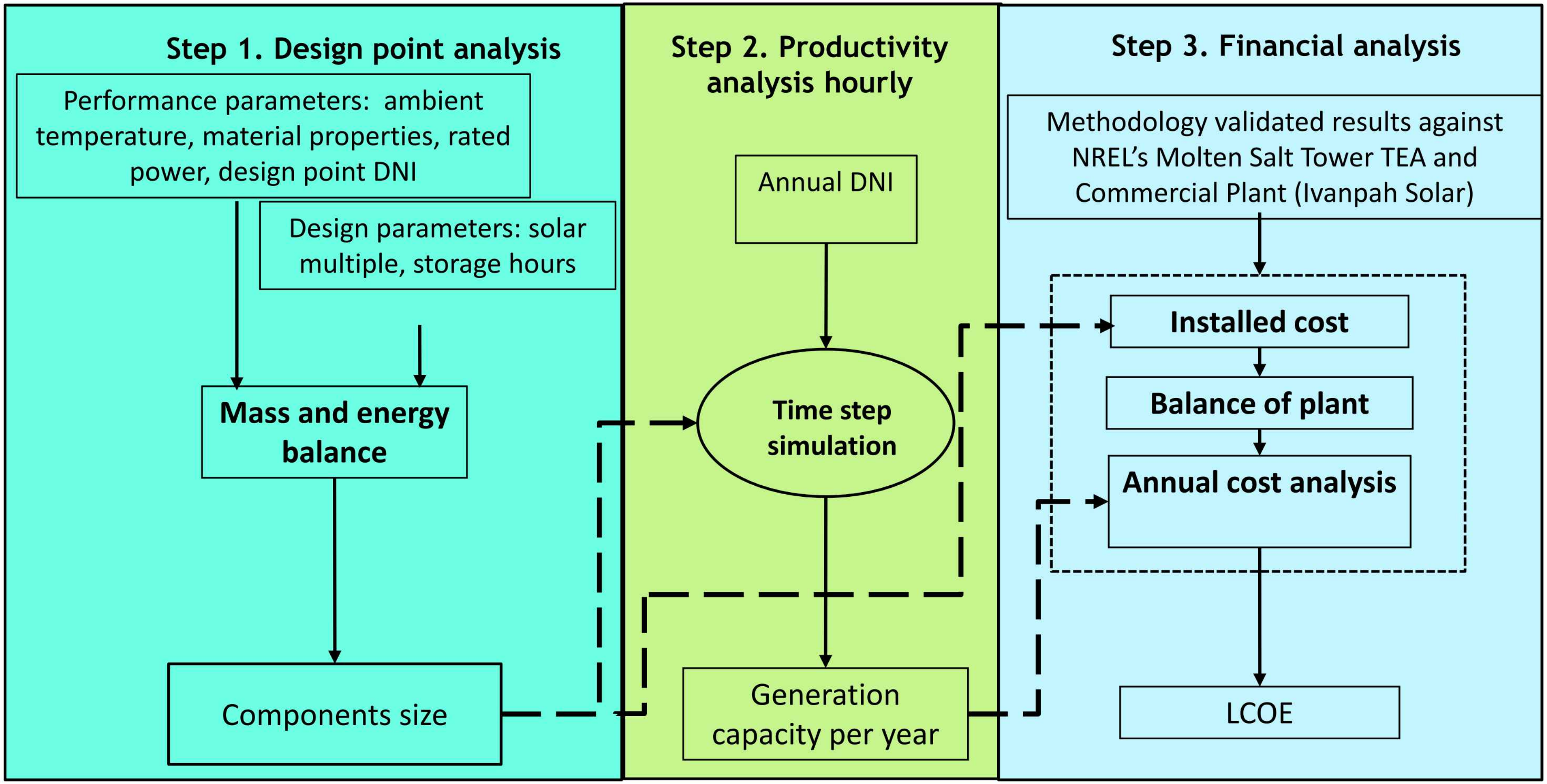


Data from these two runs used to further calibrate/validate the 1-D model

5. Technoeconomics and Systems



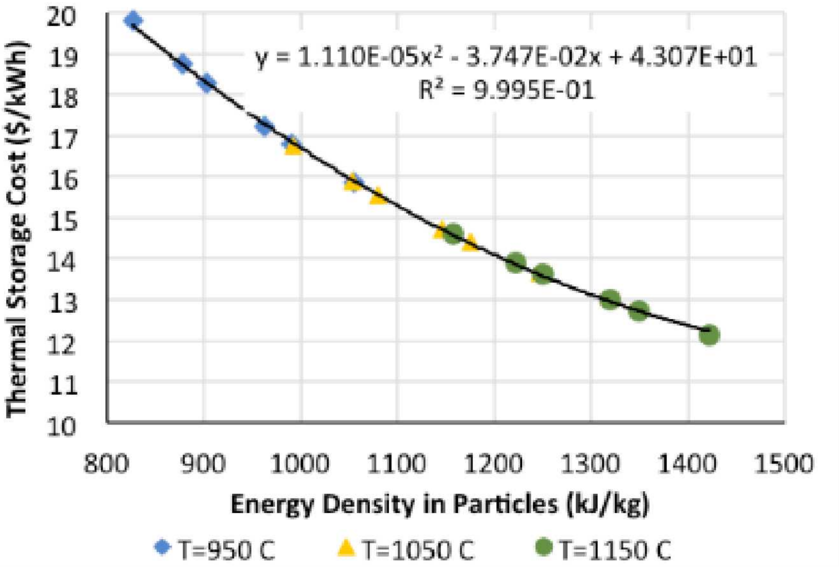
Coupled Performance and Economic Analysis Methodology



Technoeconomic Modeling

TE and performance models at various scales are continually updated and refined as new data is available. Information shown incorporates data for CAM28 and assumes a scale of 111.7 MWe.

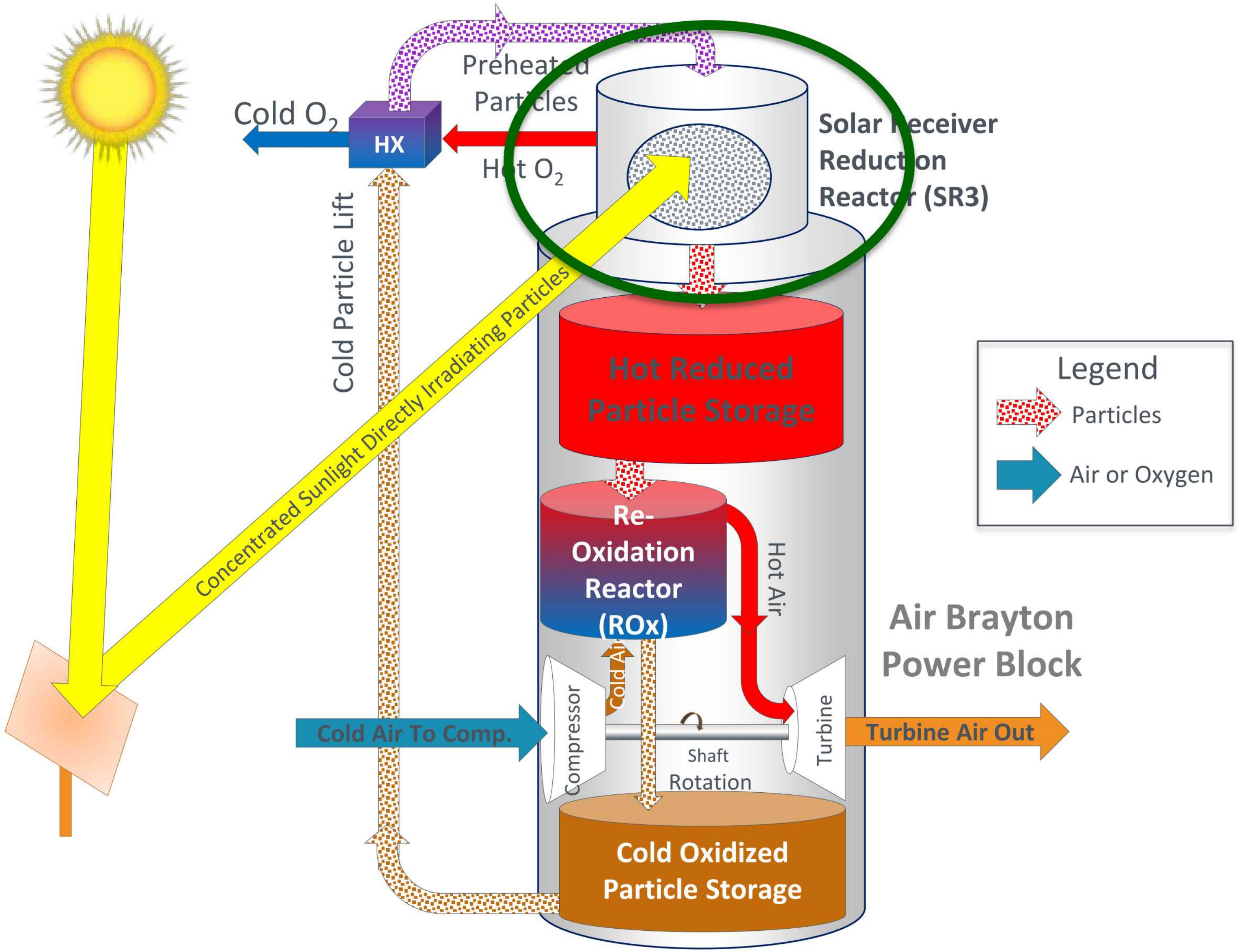
Component List	Cost	% of Total
SR3	$ 31,990,464	8.3%
Vacuum Pump	$ 26,597,883	6.9%
Particles	$ 11,123,973	2.9%
Tower	$ 10,967,142	2.8%
Elevator	$ 1,129,862	0.3%
Heat Exchange	$ 1,865,733	0.5%
Storage Hot	$ 3,593,935	0.9%
Storage Lower Hopper	$ 2,355,678	0.6%
Storage Upper Hopper	$ 1,247,124	0.3%
ROx Reactor	$ 1,696,460	0.4%
Controls	$ 3,523,857	0.9%
Solar Field	$ 68,403,311	17.7%
Power Block	$ 93,583,548	24.3%
Balance of Plant	$ 16,276,905	4.2%
Contingency & Indirect	$ 64,519,742	16.7%
Owner's Cost	$ 46,640,498	12.1%
Multiple Components/Total	$ 385,516,114	



Storage cost as a function of energy density. Data points assume CAM 28 with the energy density varying as a function of the SR3 temperature and pO_2.

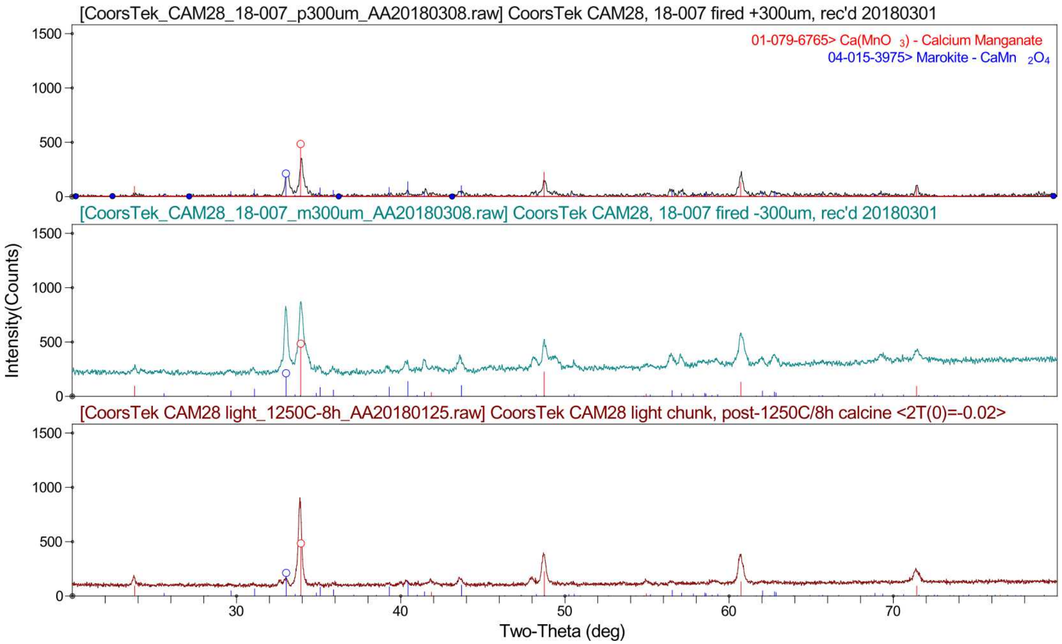
- Particle inventory sensitive to temperature of the incoming air, SR3 operation, and the fabrication factor
  - Particle cost estimated at $8.50/kWh$_{th}$ based on CAM28 reduced at 1050°C and 200 Pa pO_2 (δ=0.203), residual particle heat = 388 °C after ROx
- Storage volume scales with amount of particles, cost scales more slowly
  - Estimated at $4.60/kW$_{th}$

SR3 Scale Up and On-Sun Testing



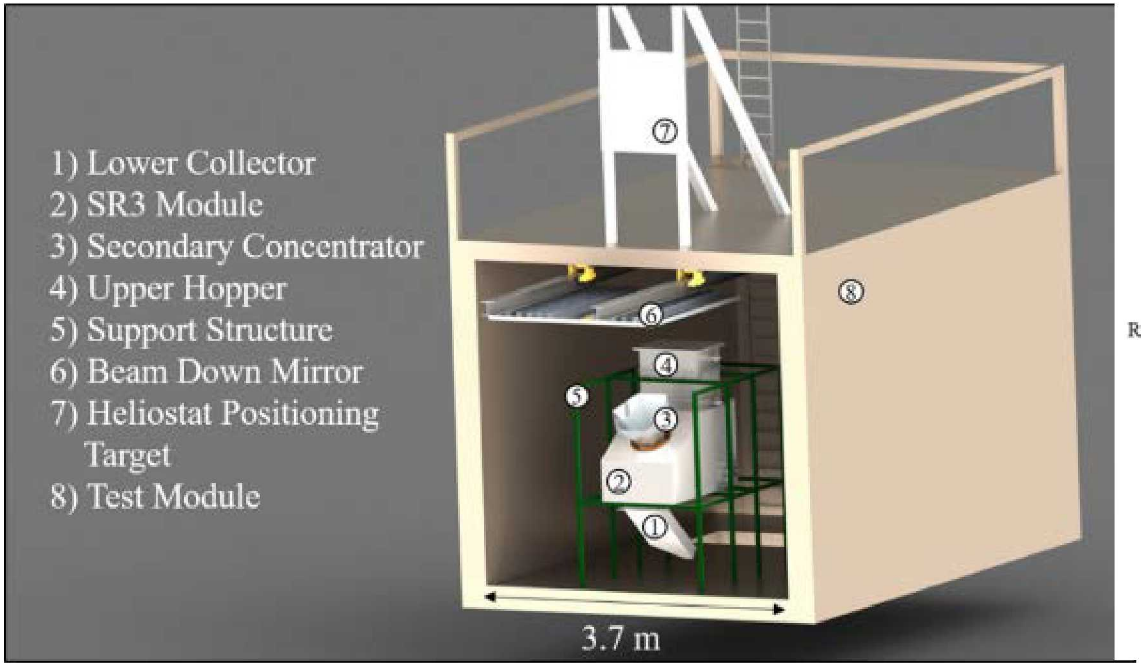
Particle Scale-up

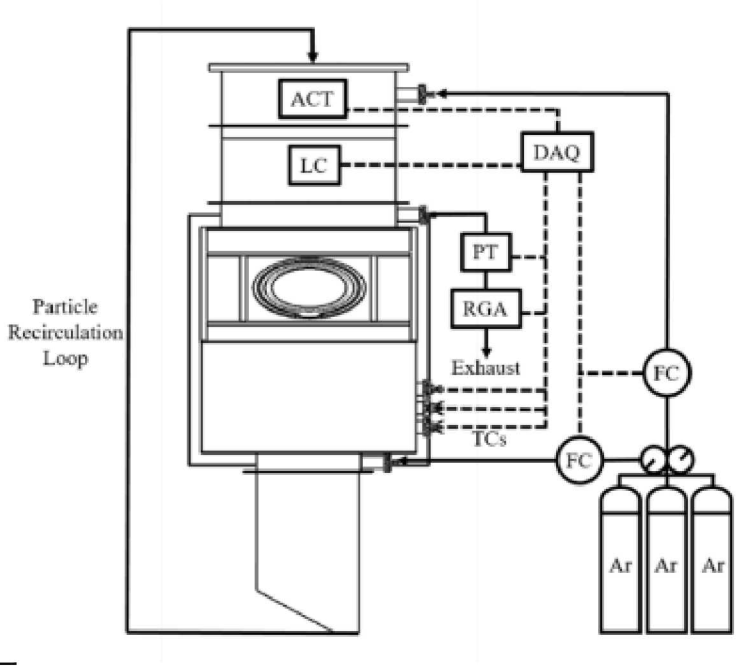
- Particle scale-up (250 kg) undertaken by CoorsTek
- Particles were spray-dried and calcined in air in static furnace
- Resulting particles were not single phase
  - Combination of spinel [$Ca(Al,Mn)_2O_4$ / $Ca_2(Al,Mn)O_4$] and perovskite phases
  - Spinel is not as redox active as the perovskite, impacts the redox efficiency of the bulk material
  - Hypothesis: not enough O_2 reached the bottom of the reaction crucible resulting on oxygen-deficient spinel phase
- Exact effect of mixed phase on 100 kW on-sun test is uncertain



Scale-up 100 kWth Reactor Design

- 100 kW_{th} scaled-up reactor designed, to be tested at Riyadh Techno Valley Tower at King Saud University
- Due to scale, reactor operated in atmospheric pressure, inert Ar environment

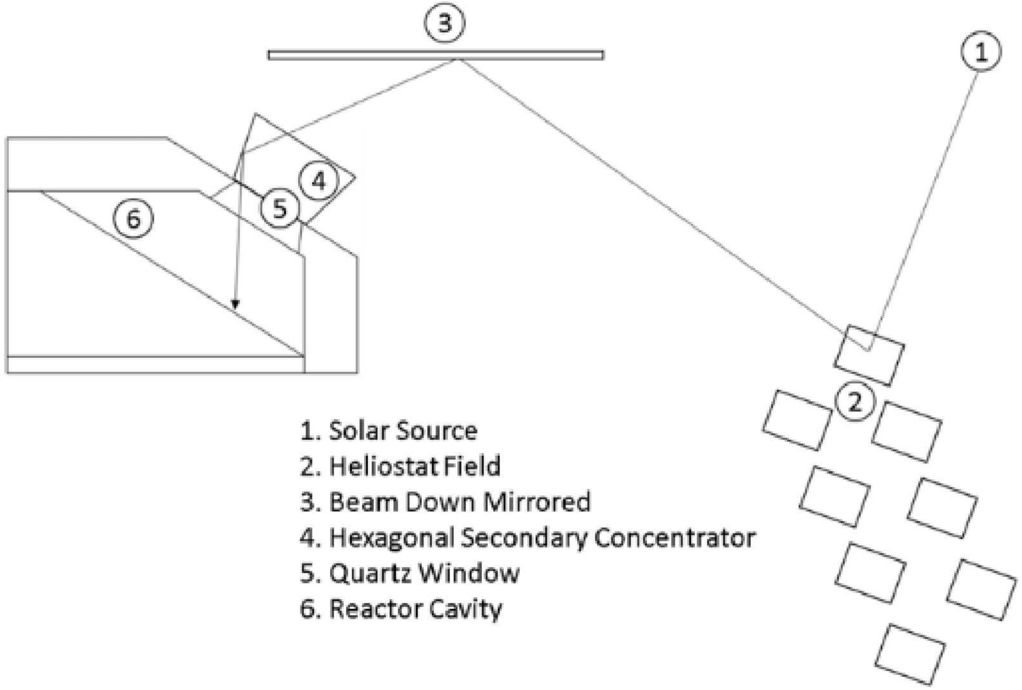




Solidworks rendering of 100 kW_{th} design mounted reactor designatop Riyadh heliostat field (left) and experimental diagram (right) of 100 kW_{th}

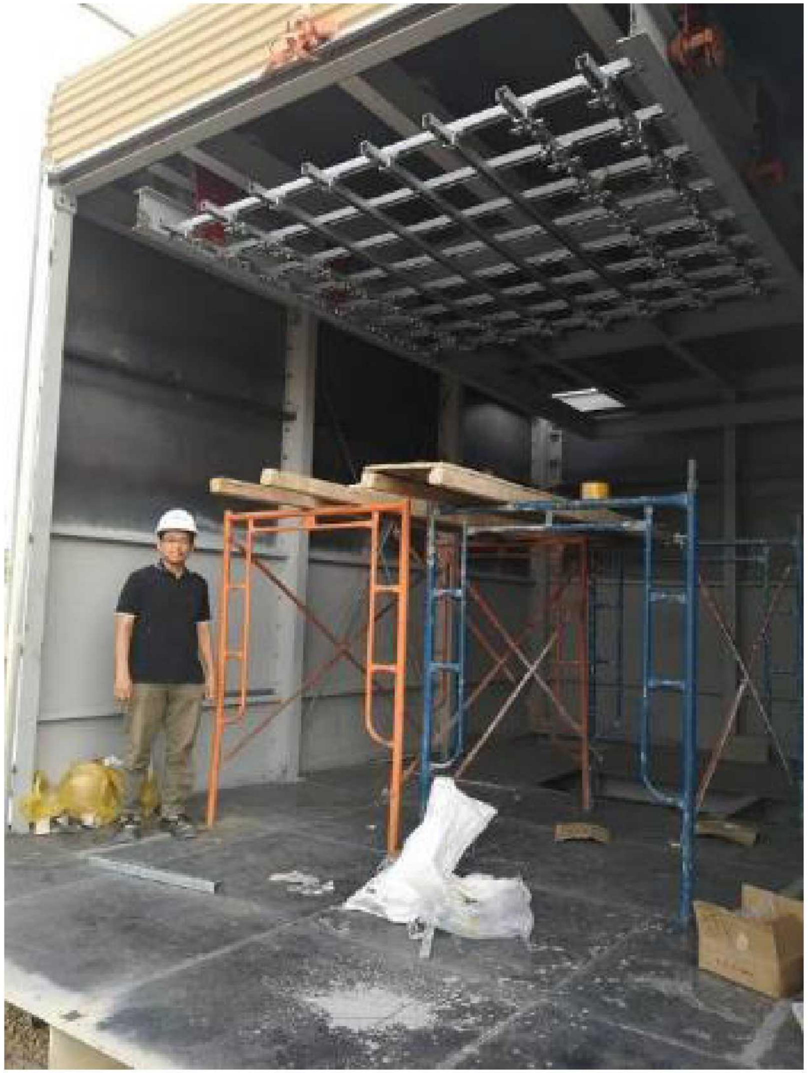
Scale-up 100 kWth SR3 – Radiation Modeling

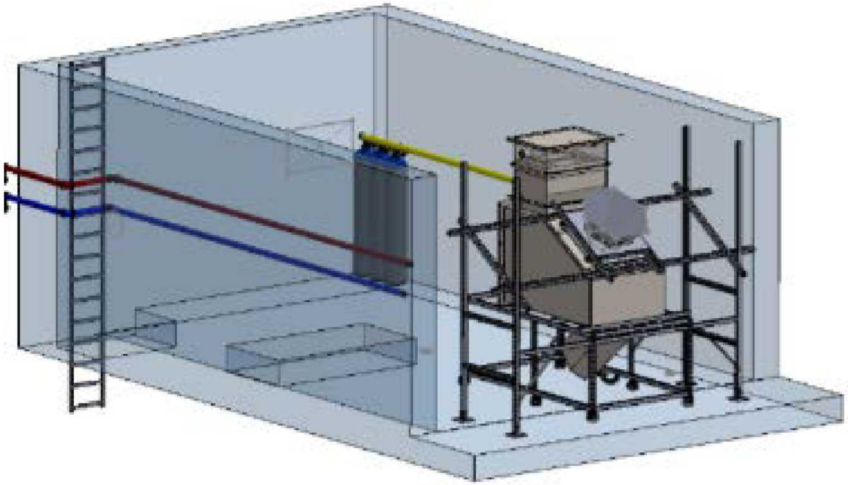
- Monte Carlo Ray Trace Model developed to capture radiative exchange from the heliostat field to the reactor cavity
- Model used to improve designs of mirrored subsystems and cavity geometry
- Model used to predict temporal, absorbed incident heat flux distributions upon inclined plane



Schematic of 100 kW_{th} field including major components participating in radiative exchange

Promotes Module Layout





Summary

- We have discovered and characterized a family of redox active MIEC oxides , CXM, which exhibit total enthalpies > 1200 kJ/kg
  - Stable at high temperatures
  - Reproducibly cycled with little loss in performance
  - Comprised of earth abundant elements
  - To our knowledge, these materials outperform any reported oxide TCES material operating above 1000 °C
- The Solar Thermochemical Inclined Granular-Flow Reactor (STINGR) constructed at Georgia Tech and tested to validate models
- Designed storage bins and identified MIEC compatible liner materials
- A counter-flow falling-particle Re-oxidation (ROx) reactor was designed and constructed at lab scale
  - Multi-phase, thermo-fluid modeling accomplished in ANSYS Fluent
- Techno-economic modeling is underway, with constant refinement as new data is obtained
  - Current results show that the storage cost goal of $15/kWhth is achievable
- 100 kW-scale SR3 reactor constructed and ready to test at RTV in Riyadh

Acknowledgments

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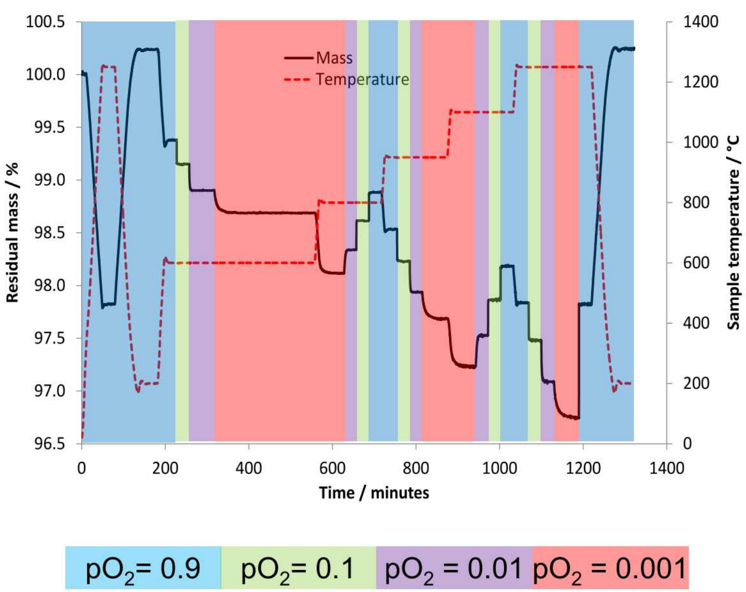
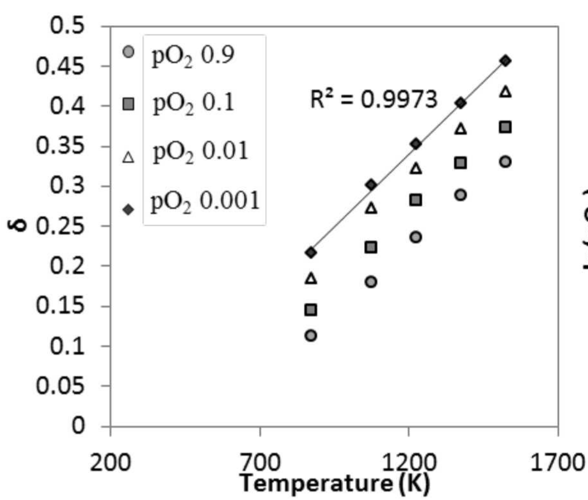
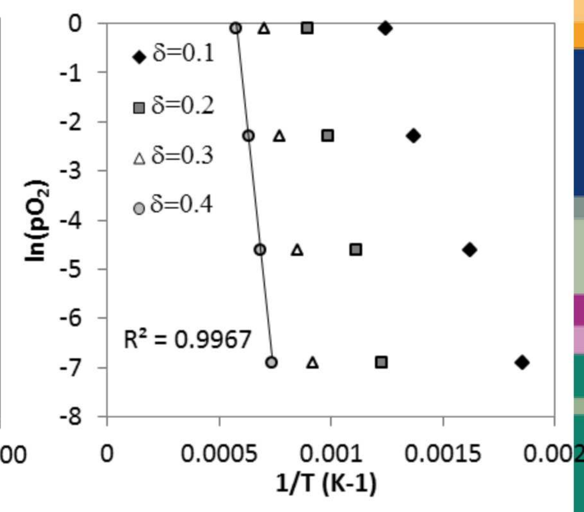
Thank You

High-resolution equilibrium TGA

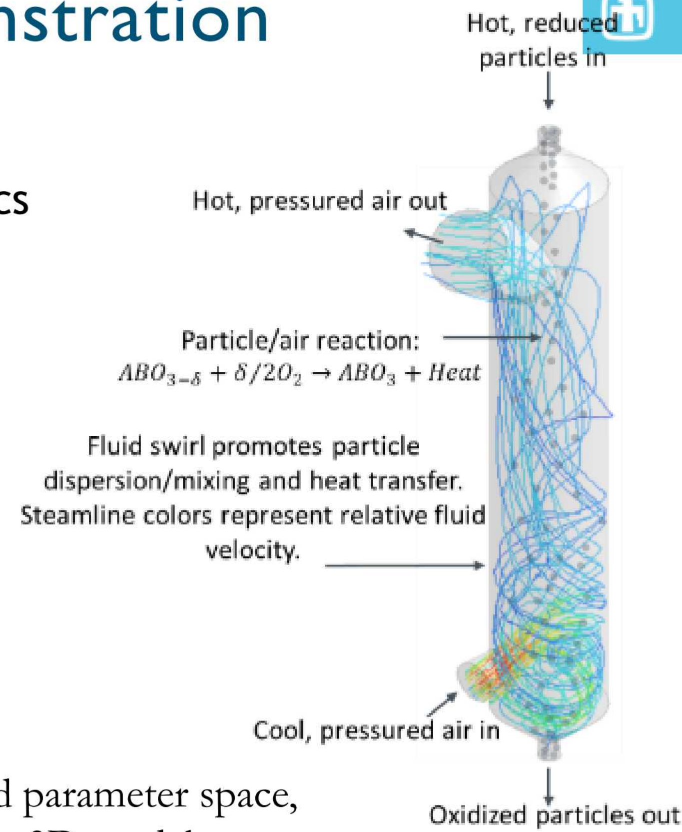
- Used to estimate thermodynamic parameters
- Isothermal holds at 600, 800, 950, 1100, and 1250 ºC; pO_2 varied at each temperature and held until equilibrium
- Thermodynamic parameters extracted by van't Hoff approach:
  - $\ln(pO_2) = 2\frac{-\Delta G_{rxn}}{RT} = 2\left(\frac{1}{T}\cdot\frac{-\Delta H_{rxn}}{R} + \frac{\Delta S_{rxn}}{R}\right)$
  - Enthalpy determined by slope, entropy by intercept for each value of δ







4. ROx: Design, Modeling, Demonstration

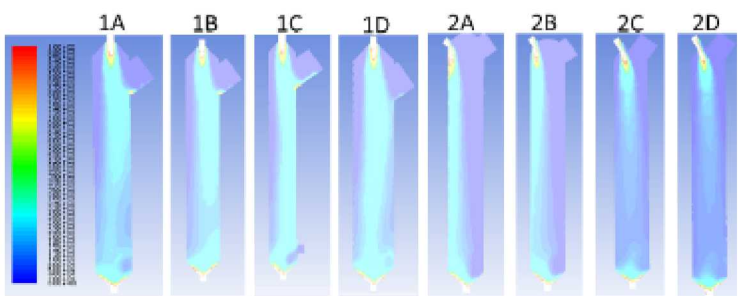


Counter-flow falling-particle design

- Flow pattern optimizes heat transfer and reaction kinetics
- Low pressure drop due to dispersed particles

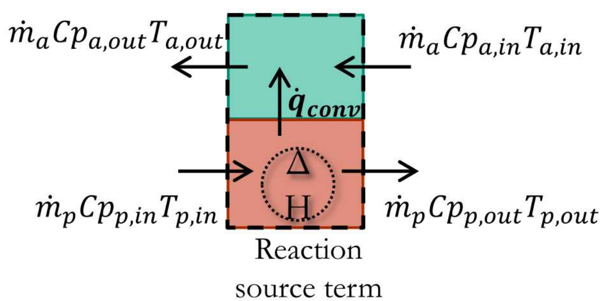
Multi-phase, thermo-fluid modeling accomplished in ANSYS Fluent (right)

- Eulerian-Eulerian approach simulates particles as equivalent "fluid"
- Granular theory used for particle motion to capture particle-particle collisions
- Custom user-defined code to implement reactions



Fabricating a lab-scale (~2.5 kW) ROx demonstration unit – geometry optimized via Fluent modeling.

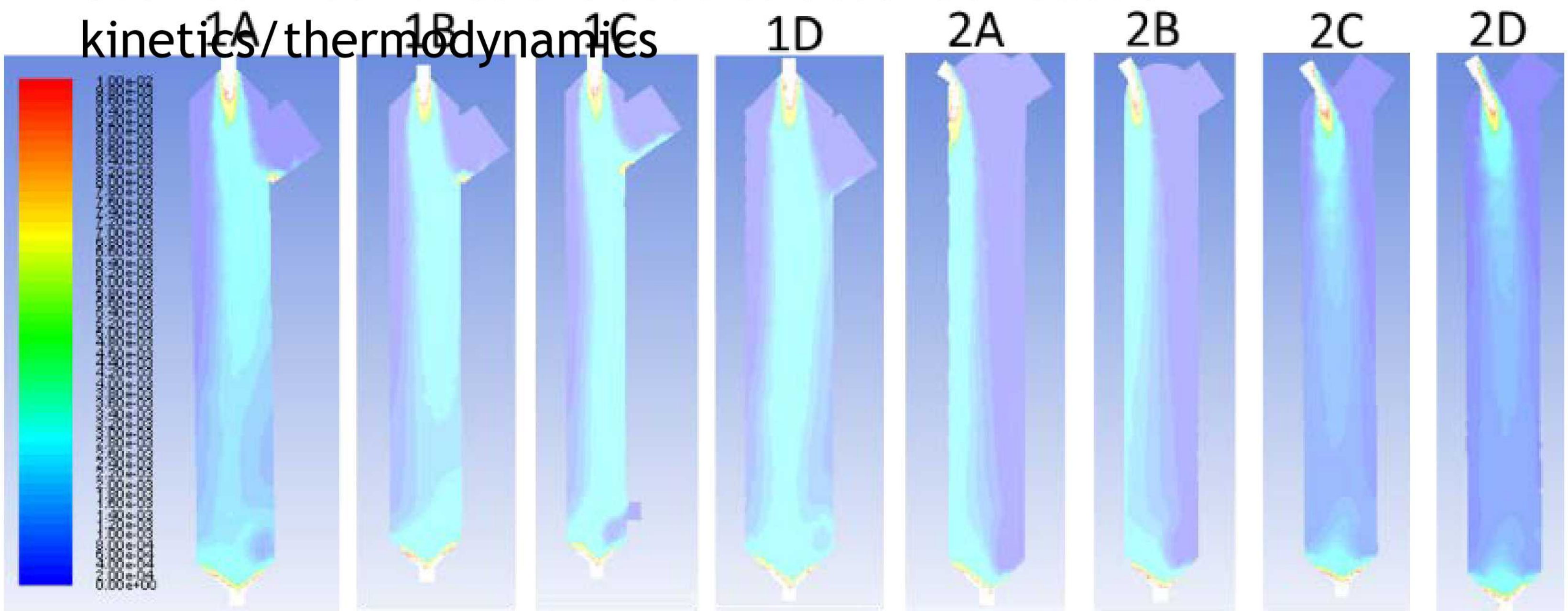
1-D model to bound parameter space, define inputs to 3D models



Functions of T: ρ_a, v_a, μ_a, Cp_a, Cp_p, Re/Nu/Pr, h, δ_{equil}

Multi-phase, thermo-fluid modeling using ANSYS Fluent applied to ROx design

- Eulerian-Eulerian approach simulates particles as equivalent “fluid”
- Granular theory implemented to describe particle motion and capture particle-particle collisions
- Multi-species approach used to quantify local oxygen consumption and particle conversion
- User-defined functions used to describe reaction kinetics/thermodynamics



Steady-state particle volume fraction for each geometry

Particle Lift and Flow Control

- The particles are lifted using an air conveyor
- The use of air ensures that the particles are fully oxidized and cooled prior to a new test run

- The particles are then dropped into the top hopper
- The outlet of the top hopper is controlled using a lift jack

SR3 Test Unit

The SR3 Test unit (RIGHT) has been constructed and is under going dry run testing at Georgia Tech.

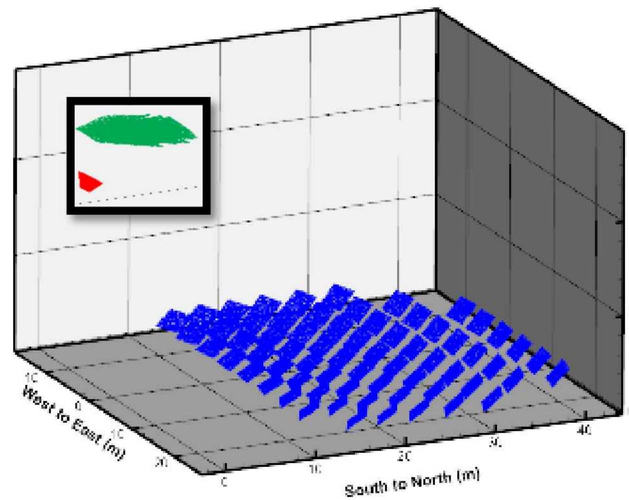
The reactor slope, and necessary insulation have been installed for the purpose of testing, seen below.

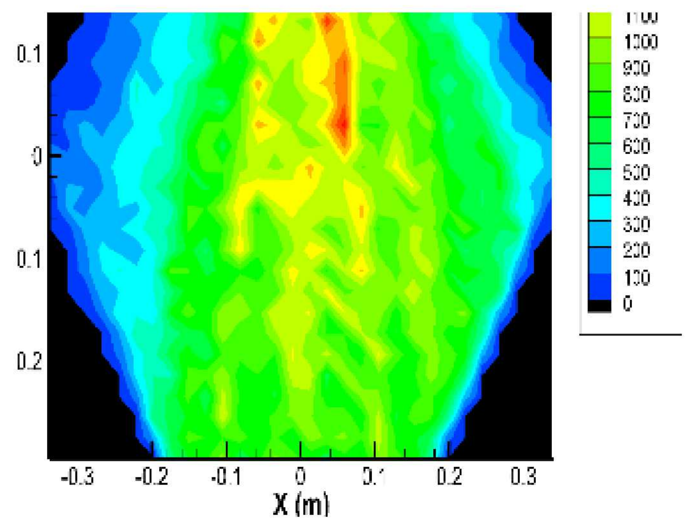
SolTrace Modeling for the 100 kWth Reactor Design

SolTrace estimated the performance of the RTV field and informs the design parameter for the beam down mirror and the secondary concentrator.

The resulting flux maps are used to predict the irradiance into the SR3 and the expected heat loads on the beam down and secondary concentrator surfaces.

The raytracing data is being used in ANSYS to model the SR3.





Secondary Concentrator Design

The secondary is used to concentrate a 400 sun flux over 1 m x 1 m target to over 1000 suns in 0.3 m diameter aperture.

The secondary is made of 6 polished aluminum cold plates.

Each trapezoidal cold plate utilizes 1.5 GPM of water to keep the system adequately cooled.

Beam Down Design

The beam down mirror is made of a series of smaller facets arranged into a 2.1 m x 2.1 m

Each facet is 0.3 m x 0.3 m and will be cooled using forced convection.

The small size and additional cooling mitigate thermal stresses to a manageable level.