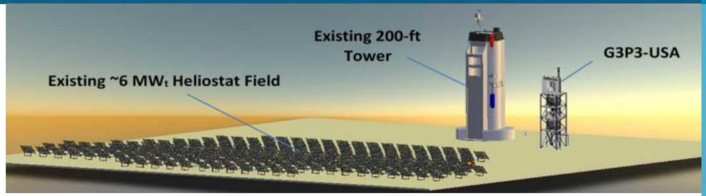
Sandia National Laboratories

SAND2020-4772PE

SOLAR THERMAL TECHNOLOGIES: NEXT GENERATION POWER AND OTHER NOVEL APPLICATIONS



Lindsey Yue, PhD

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

U.S. DEPARTMENT OF ENERGY

NNSA

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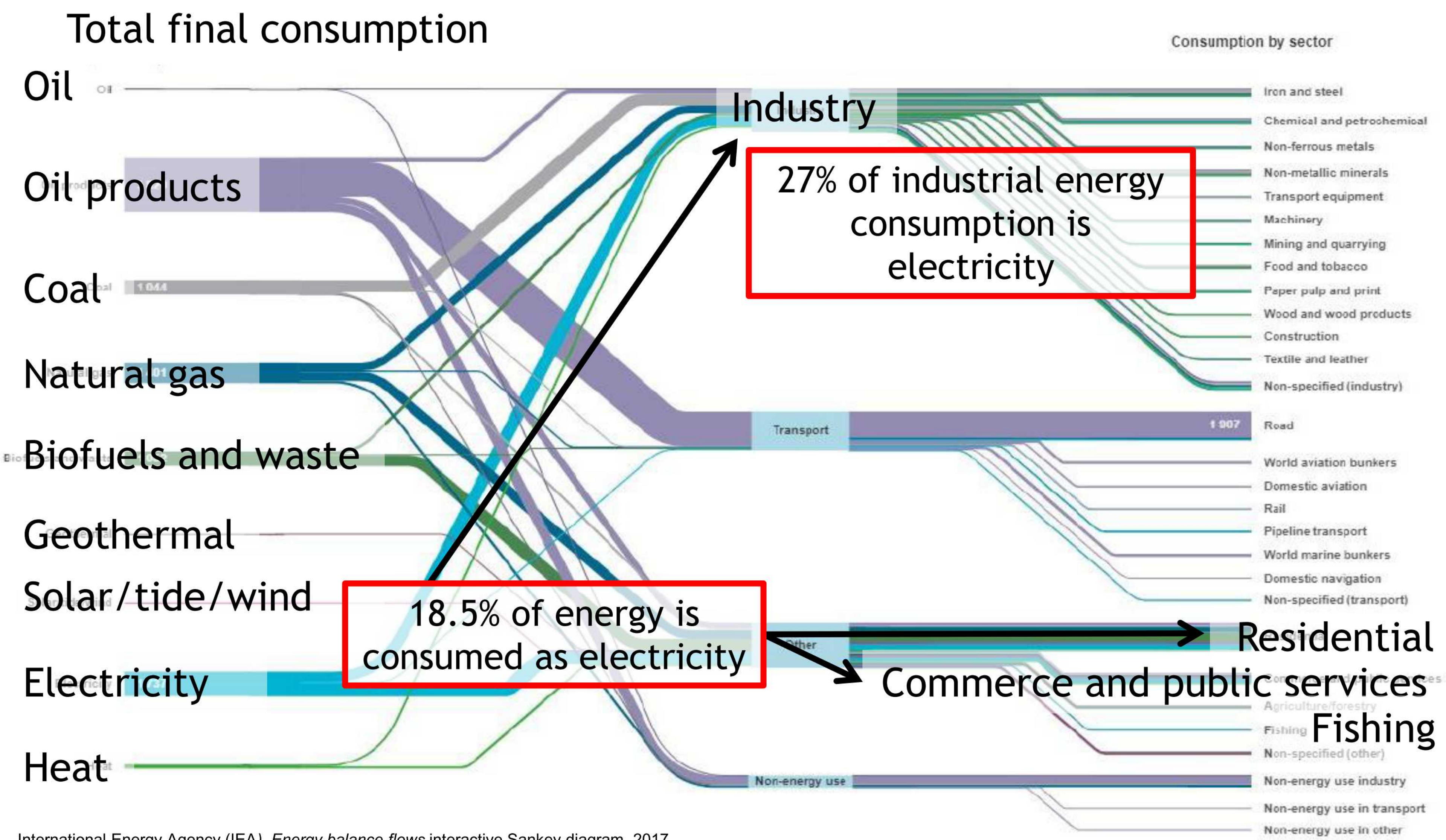
Outline

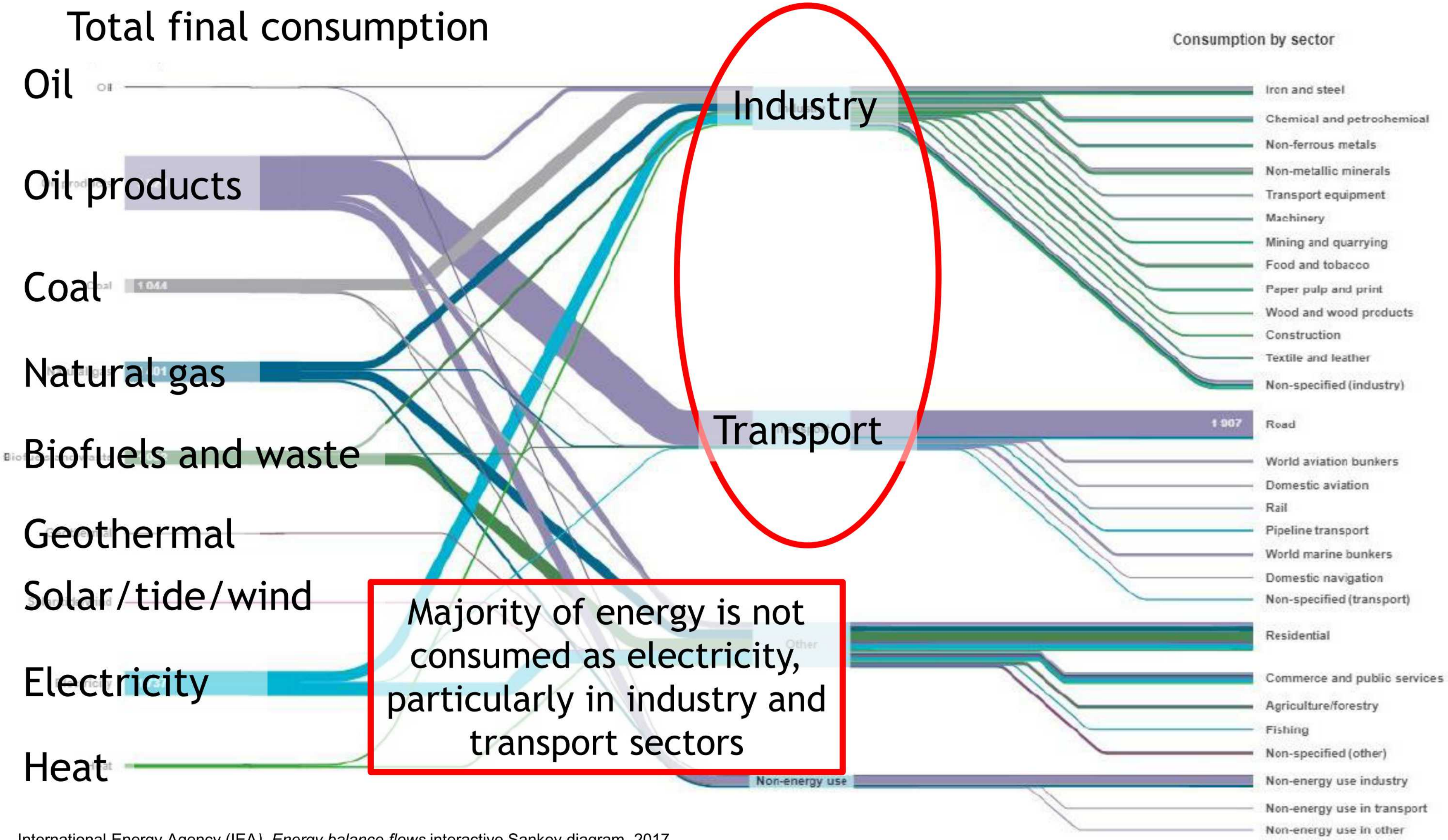
- Motivation for diverse solar thermal energy technologies
- Next generation particle-based concentrated solar power (CSP) technologies
- Concentrated solar thermal (CST)-driven chemical looping for non-electricity applications
- Future research directions
- Diversity in research and teaching to achieve diverse energy technology goals

Energy market



International Energy Agency (IEA), *Energy balance flows* interactive Sankey diagram, 2017.

Energy market



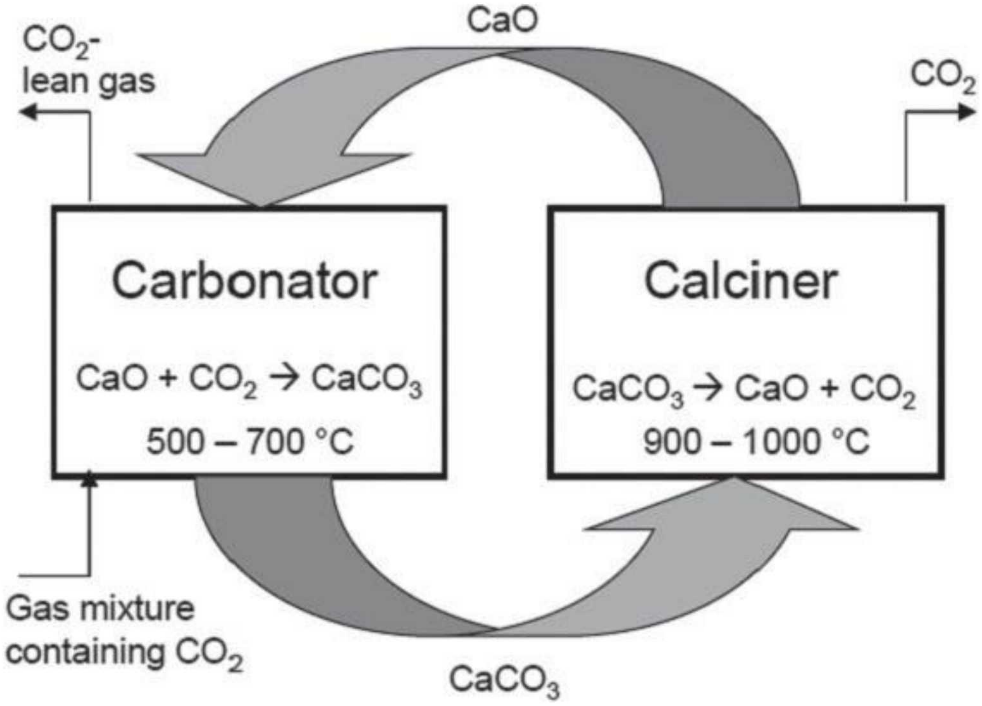
International Energy Agency (IEA), *Energy balance flows* interactive Sankey diagram, 2017.

Research experience

Next generation particle-based CSP technologies (Postdoctoral research)

Cliff Ho

CST-driven chemical looping for non-electricity applications (PhD research)



Phalak et al., *Chem Eng Technol*, 2013.

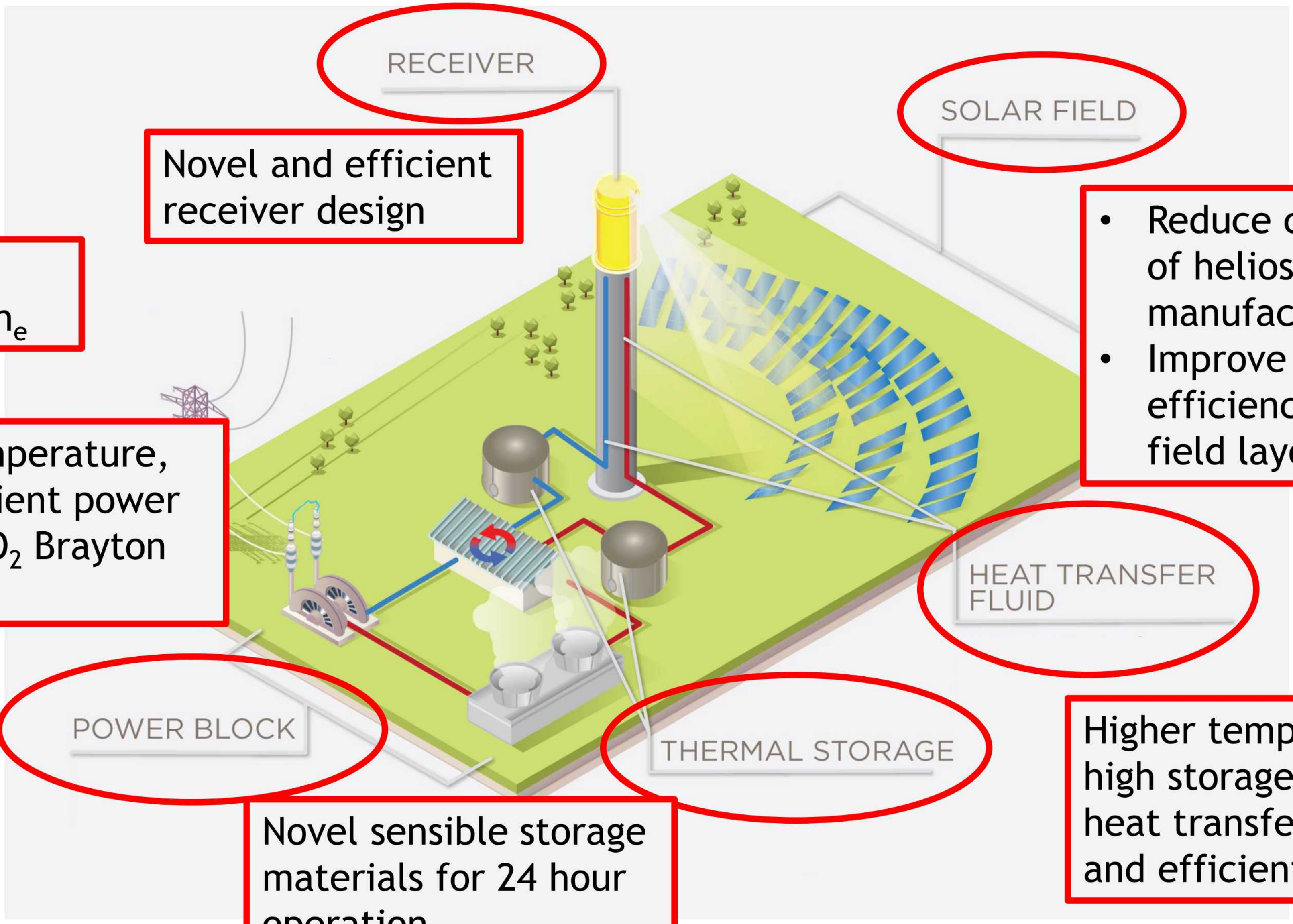
Gen 3 CSP

US DOE Sunshot goal: \$0.20/kWh$_e$

Novel and efficient receiver design

- Reduce cost of heliostat manufacturing
- Improve optical efficiency of field layout

Higher temperature, more efficient power cycles (sCO_2 Brayton cycle)

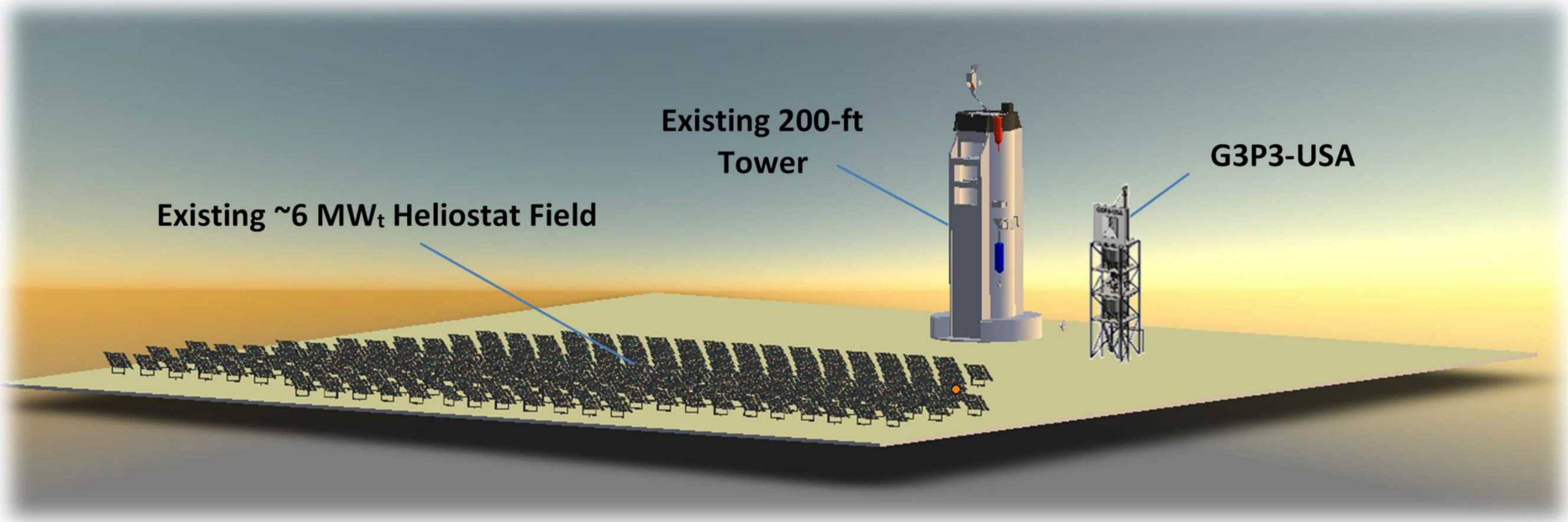


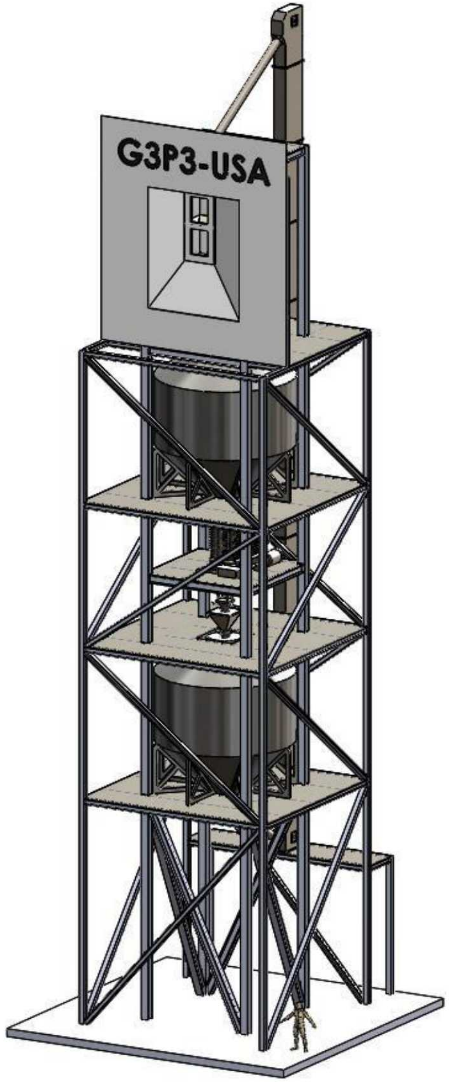
Higher temperature, high storage capacity heat transfer media and efficient HXs

Novel sensible storage materials for 24 hour operation

US DOE, Sunshot Initiative, 2

Gen 3 Particle Pilot Plant (G3P3) project





The Gen 3 Particle Pilot Plant (G3P3) is currently being designed for realization at the National Solar Thermal Test Facility. The plant uses small, sand-like ceramic particles as the heat transfer medium.

Project in-line components include:

- 1 MW$_{th}$ cavity receiver
- Hot and cold storage bins
- Particle-to-supercritical CO_2 heat exchanger
- Particle handing system

G3P3 receiver overview

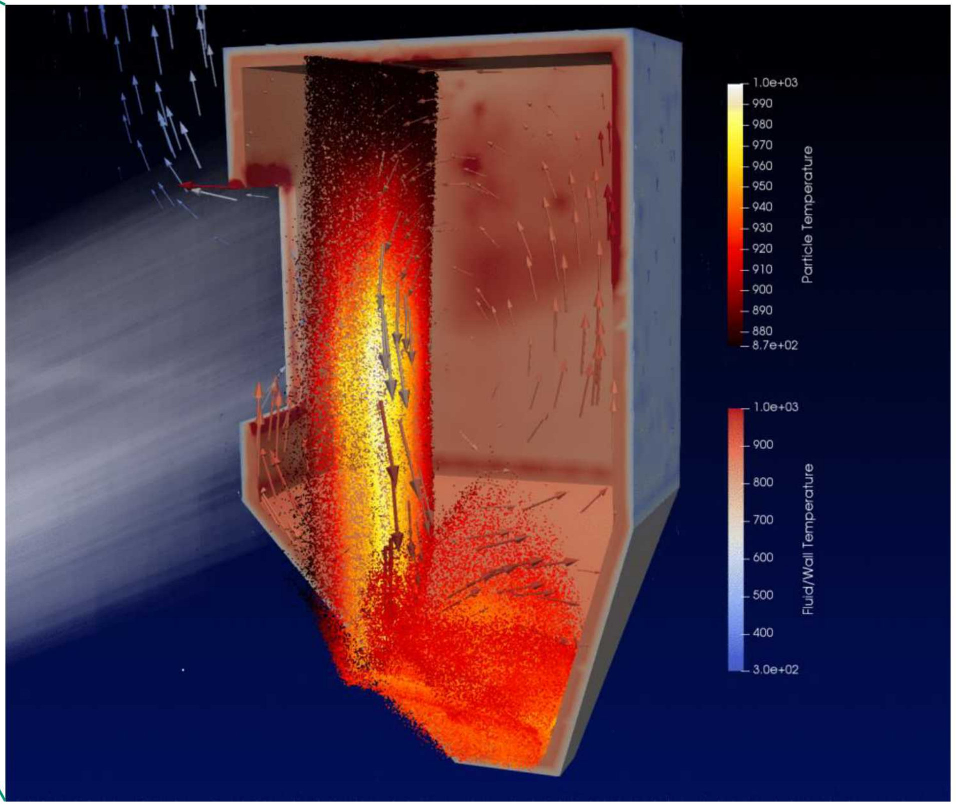
Falling particle receiver: a curtain of particles falls through the cavity

Potential to operate at higher temperatures:

- Increasing the maximum potential power cycle efficiency
- Increases heat losses through the aperture

The dominant heat loss mechanism is hot air escaping out of the receiver aperture.

Example of a falling particle receiver geometry

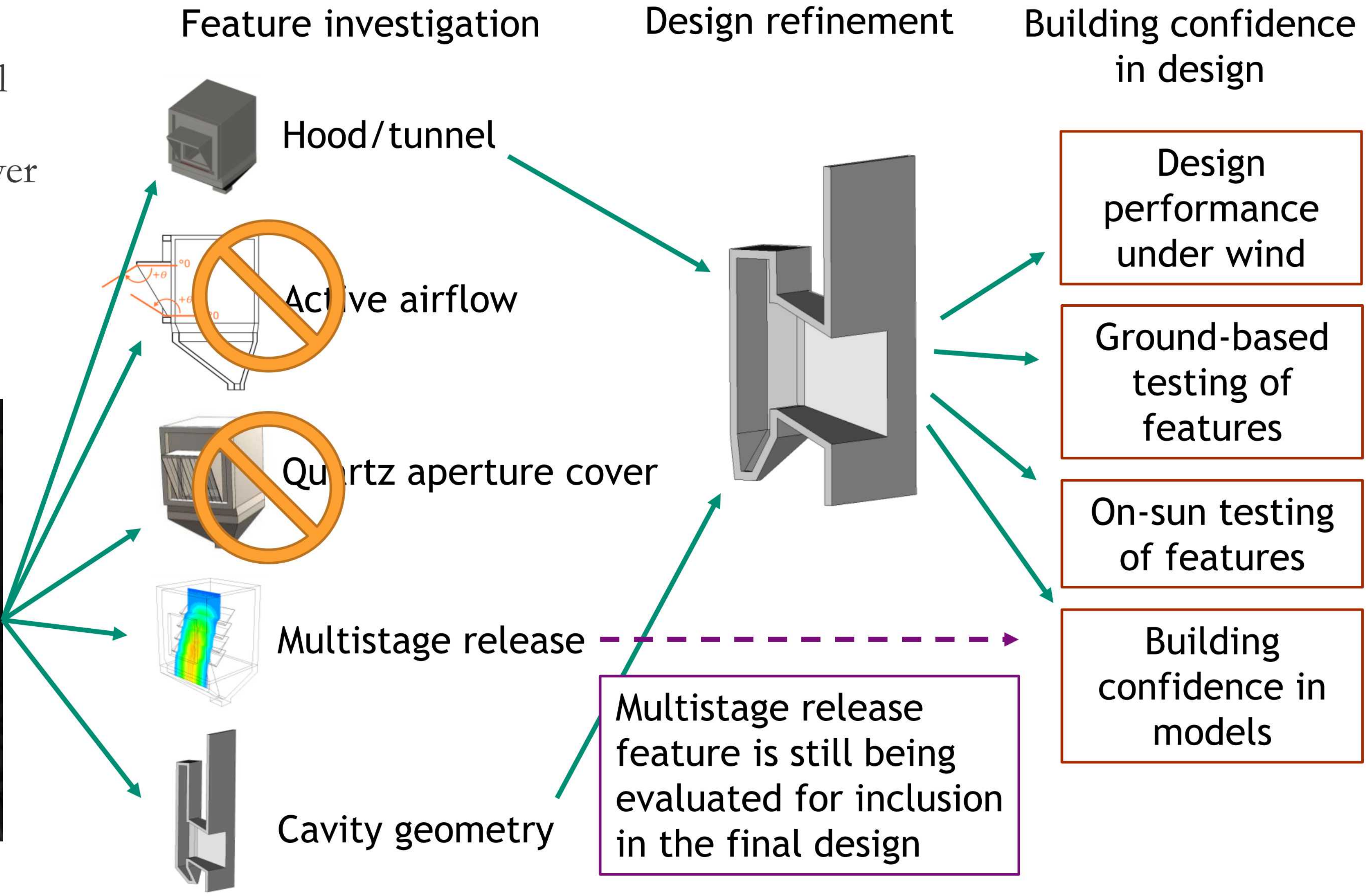


Brantley Mills

G3P3 receiver research overview

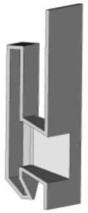
Receiver research: CFD modeling and experimental investigations to design a 1 MW_{th} falling particle receiver with >90% efficiency

Existing 1 MW_{th} falling particle receiver



G3P3 receiver research overview

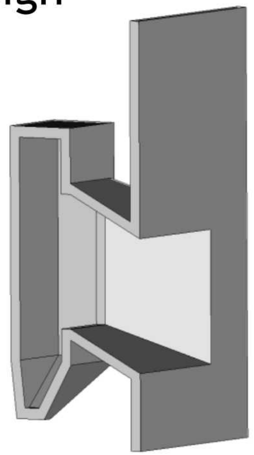
- Research over the last 1.5 years has resulted in two published and five accepted for publication conference papers
- Today, I'll be giving a brief overview of these aspects of the work:



Cavity geometry optimization

→

Current G3P3 receiver design



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Ground-based testing of features (in progress)

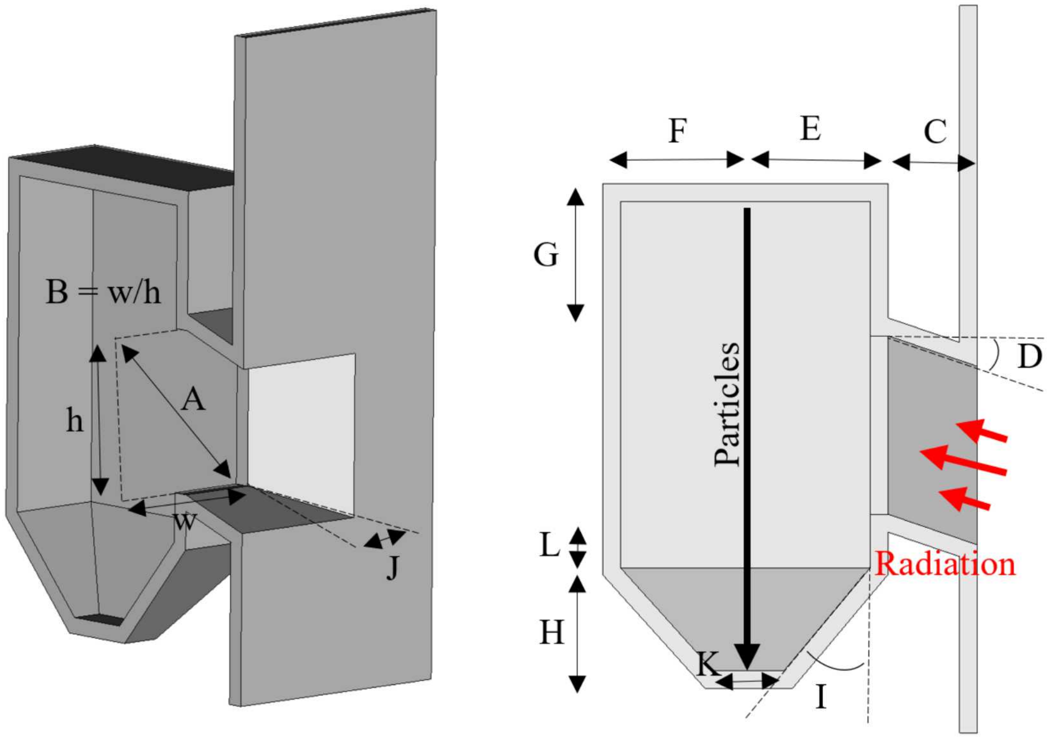
On-sun testing of features (planned)

Cavity geometry and tunnel features

A optimization study was performed varying 12 geometric parameters of the receiver cavity and tunnel

Goal: to identify a geometry that **minimized advective losses**

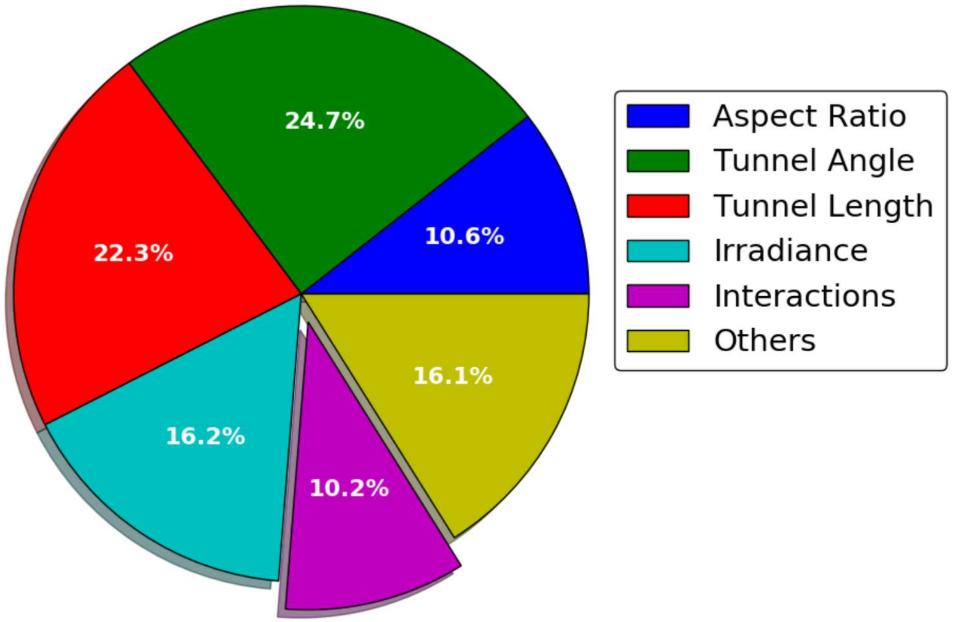
An incremental LHS study was used to investigate the geometric parameter space



Item	Description
A	Aperture Area
B	Aperture Aspect Ratio
C	Tunnel Length
D	Tunnel Angle
E	Curtain Depth
F	Behind Curtain
G	Header
H	Hopper Depth
I	Hopper Angle
J	Width Multiplier
K	Hopper Exit Size
L	Below Aperture

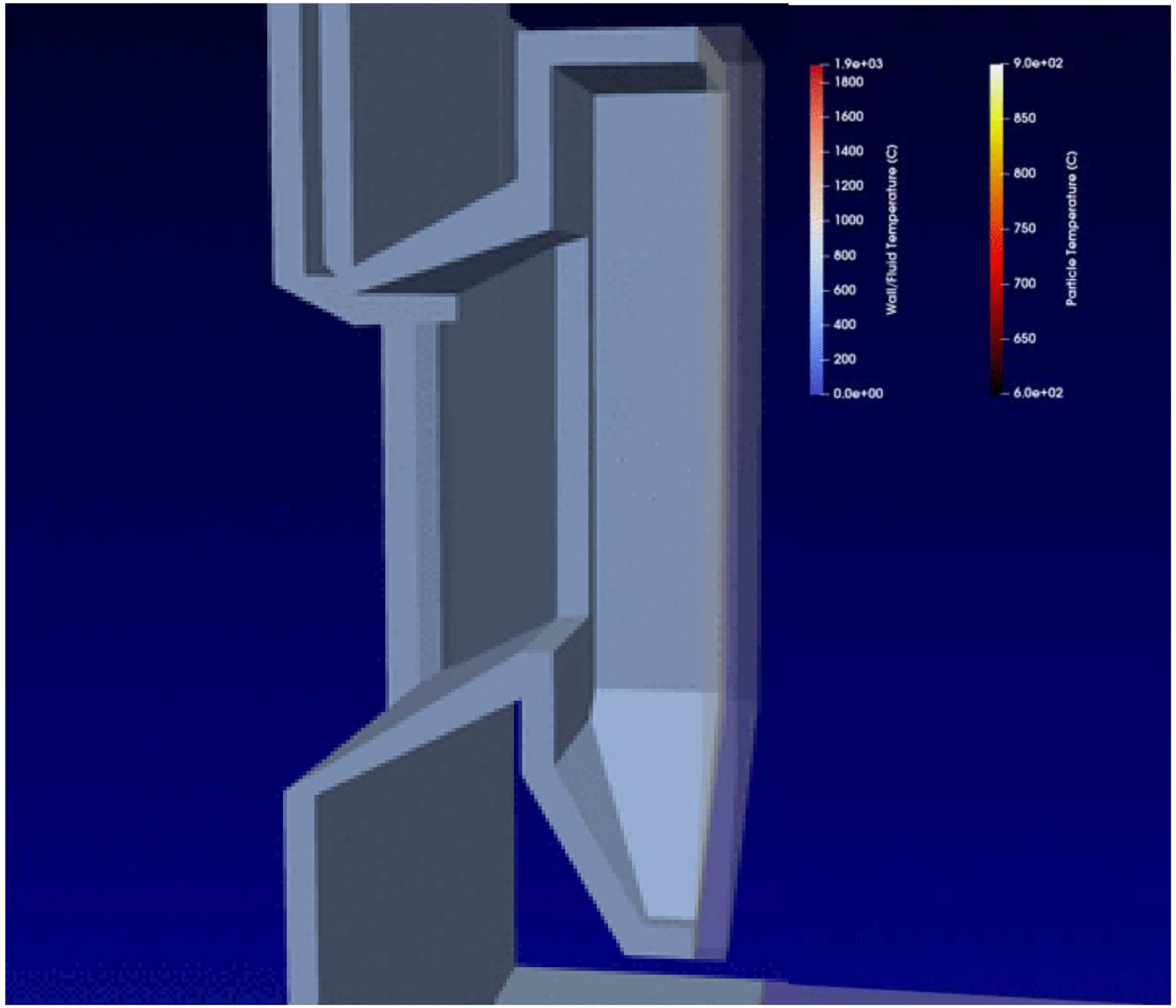
Cavity geometry and tunnel features

- LHS study resulted in 360 receiver geometry realization
- A simplified CFD model was used to evaluate the advective losses of each realization
- A linear polynomial model was fit to the advective loss results of the realizations
- A global, pattern-search optimization algorithm was used to find the optimal design from the linear polynomial model
- Sobol indices were also calculated from the LHS study and evaluated advective loss results to identify the geometric parameters that most contributed to minimizing advective losses



G3P3 receiver design

- Tunnel (SNOUT) and reduced volume cavity passively reduce advective loss
- Chimney integrated into SNOUT offers pathway to recovering advective loss and capturing particle fines



Brantley Mills

Building confidence in receiver design

Ground based testing:

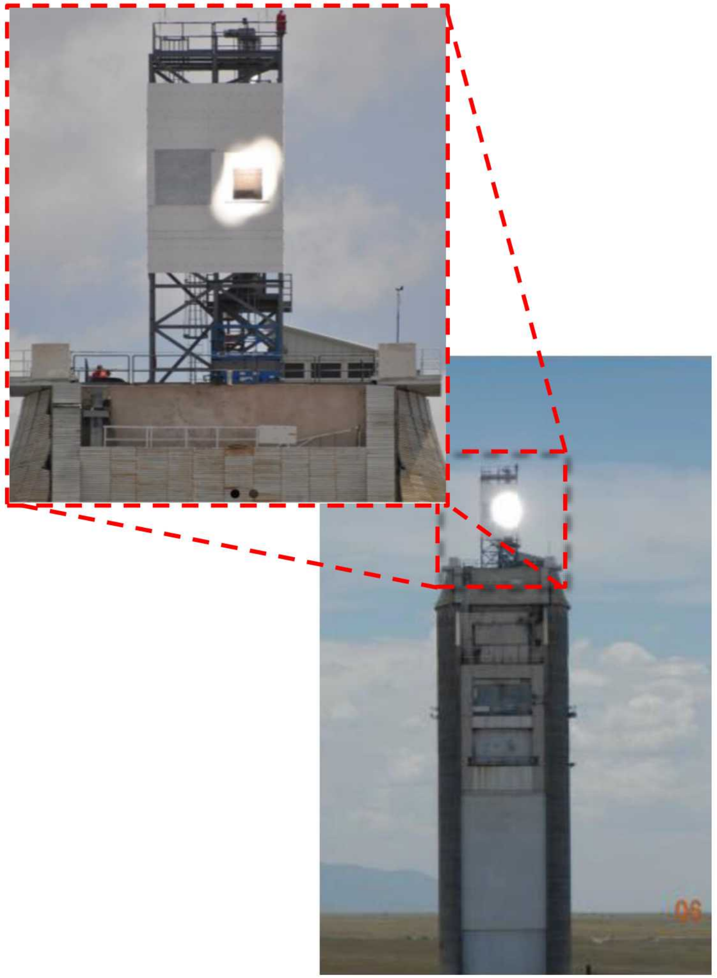
- Retrofit key G3P3 receiver features to existing receiver and measure advective loss in the absence of wind
- SNOUT and reduced volume feature evaluation complete
- Multistage release feature evaluation is in progress

On-sun testing (planned for April/May 2020):

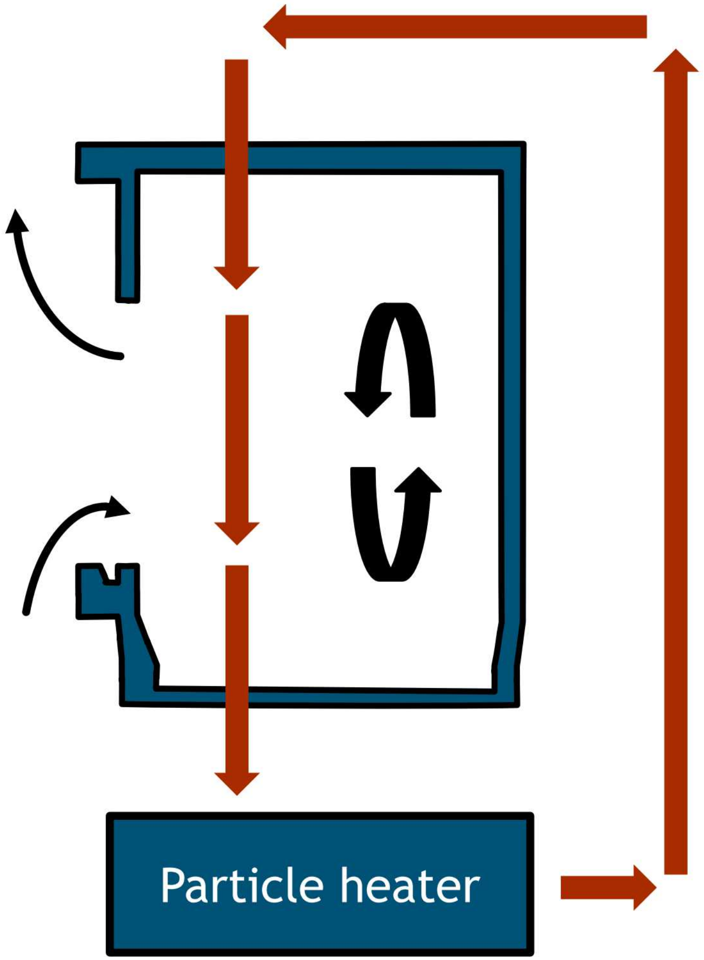
- Improve experimental plan and data collection to address challenges of previous data analysis and model comparisons
- Evaluate key G3P3 receiver features on existing receiver

Ground based testing

On sun testing



Ground based testing



Dropped hot particle curtain through receiver to heat receiver and develop air flow and advective loss representative of on-sun operation

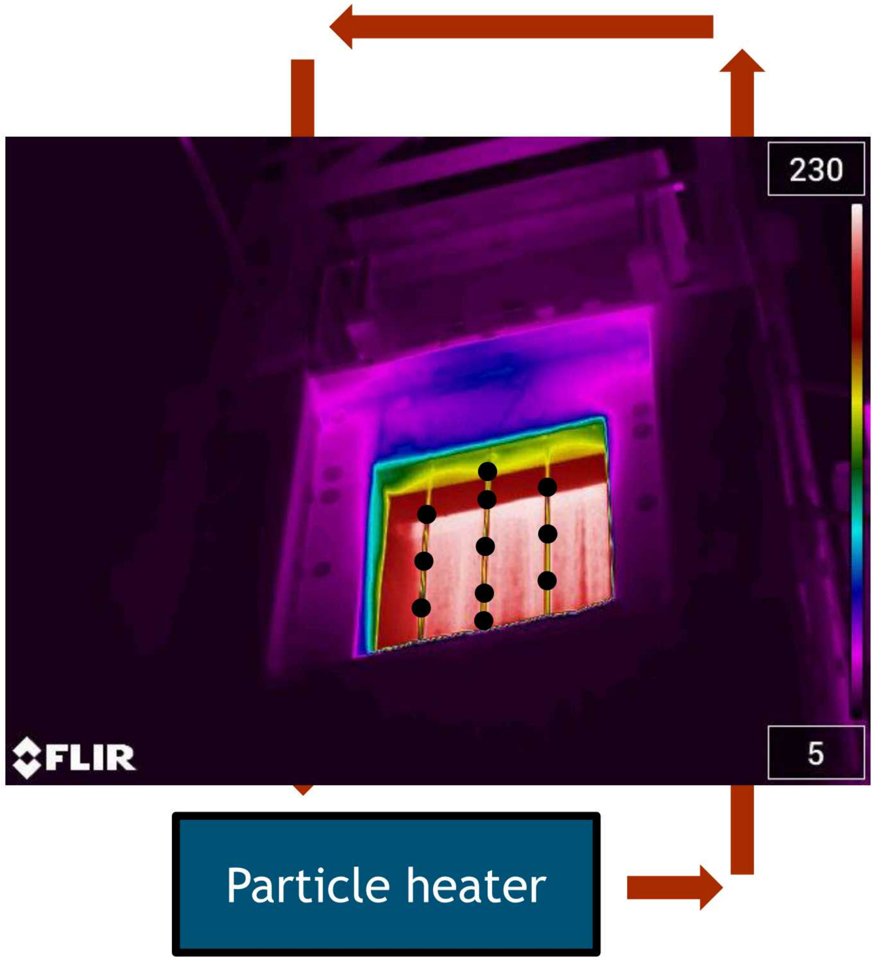
Controlled conditions (electric heater, inside tower) to provide data for comparison to CFD model

Measured temperature and velocity at 11 points at the aperture to evaluate advective losses

Tested 4 configurations to build confidence in feature ability to reduce advective loss:

Baseline (no features)	SNOUT
Reduced volume	SNOUT+reduced volume

Ground based testing



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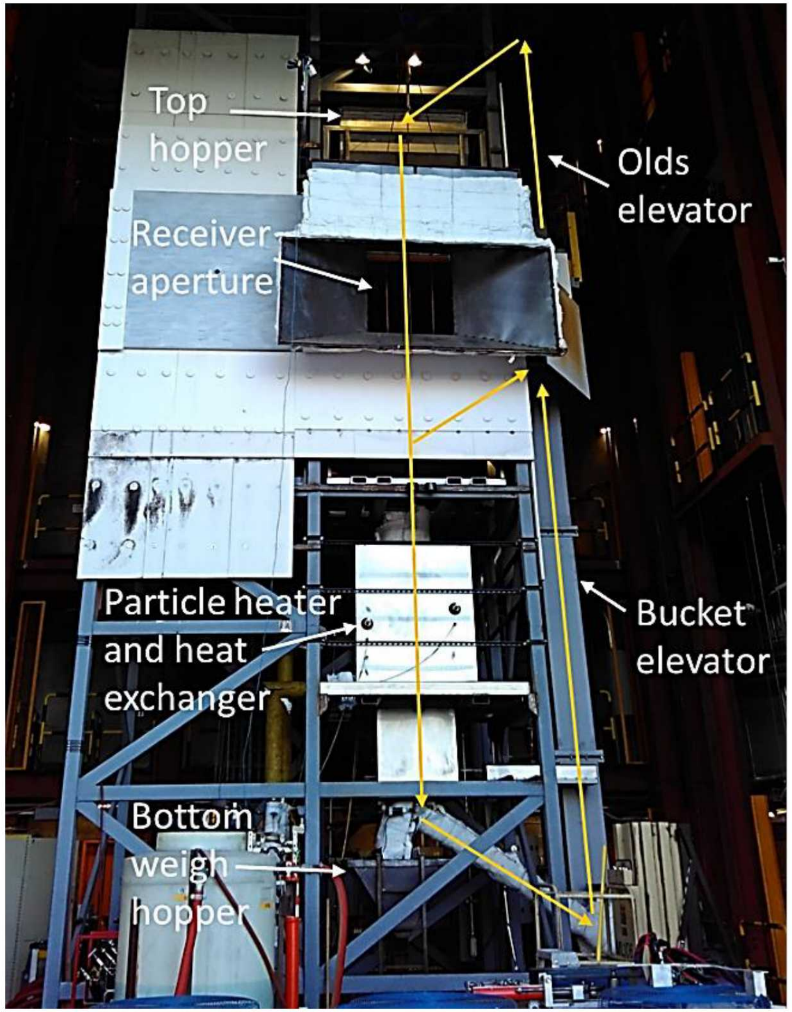
Ground based testing

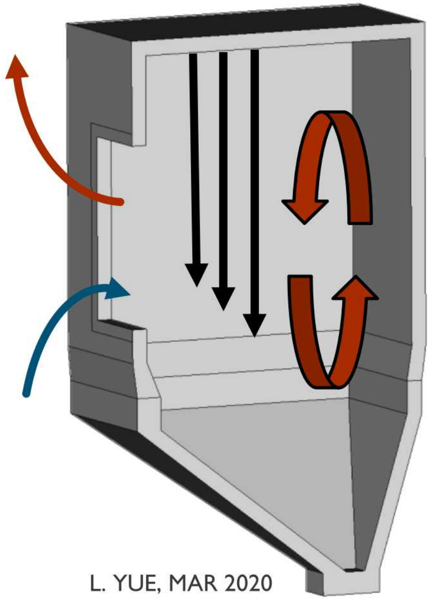
Receiver and particle flow loop



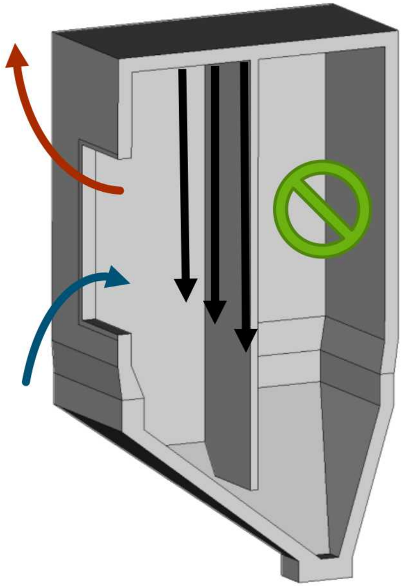
Baseline

SNOUT

Baseline



Reduced volume receiver



L. YUE, MAR 2020

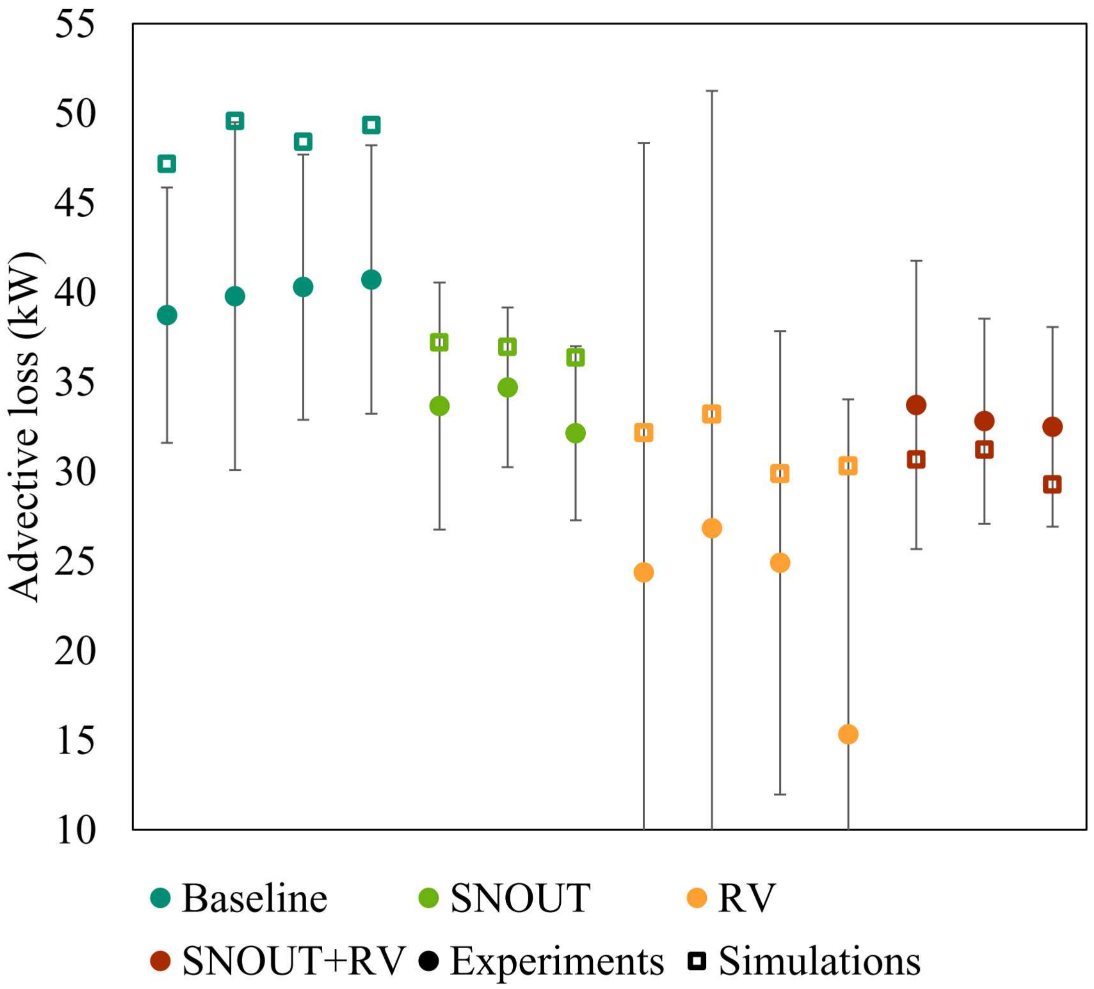
Ground based testing results

Advective loss is calculated from temperature and velocity measurements at the aperture

Advective losses are lower for all cases with features than the baseline cases

Particle mass flow rate and temperature at receiver inlet were used as boundary conditions to CFD model to predict advective loss

Numerical results for advective loss show some agreement with experimental results



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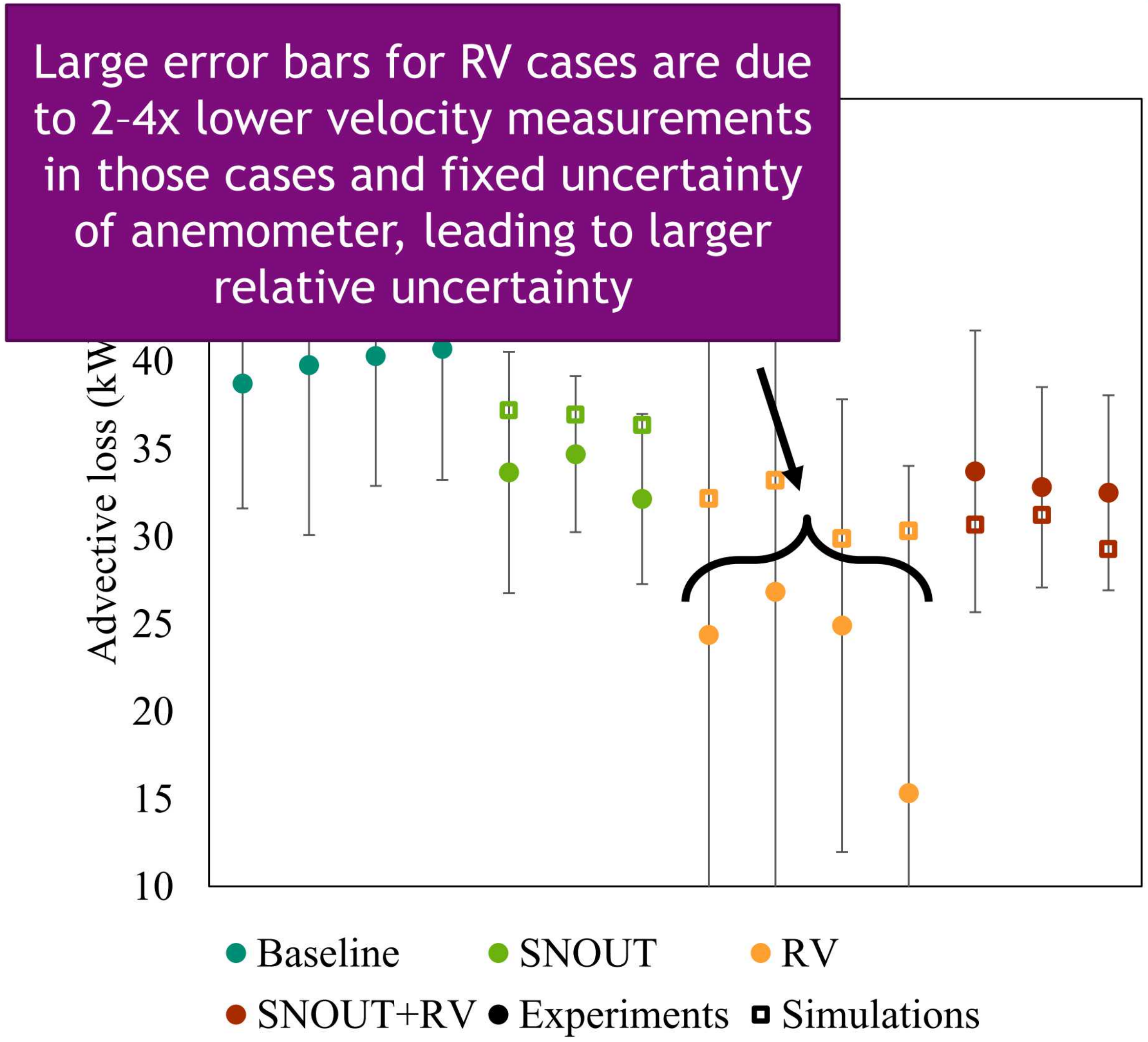

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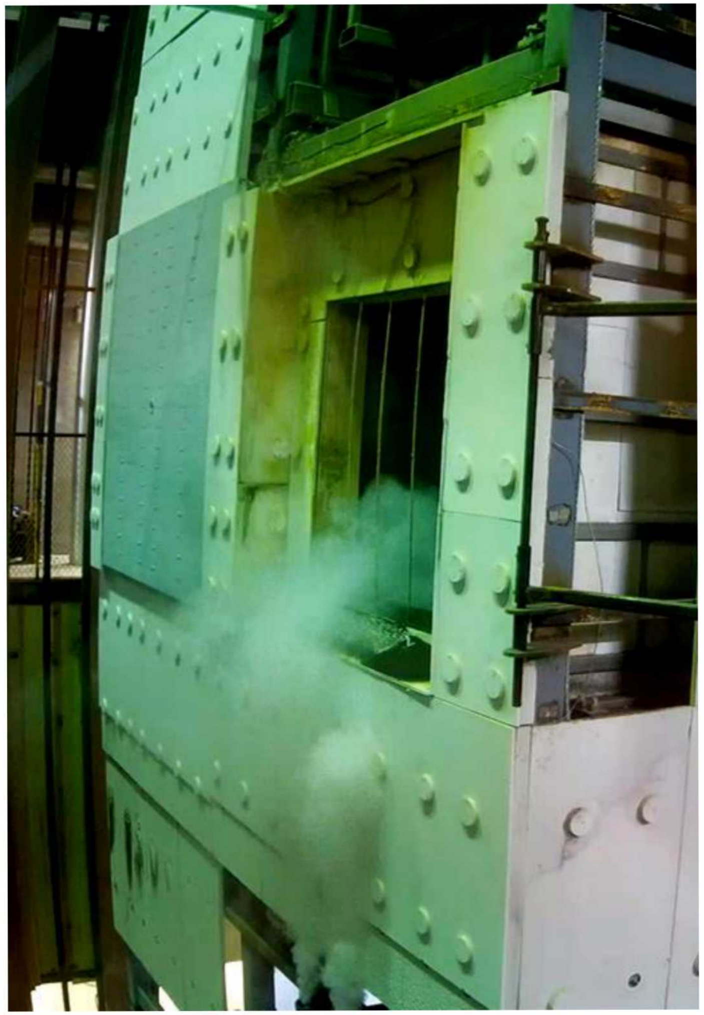
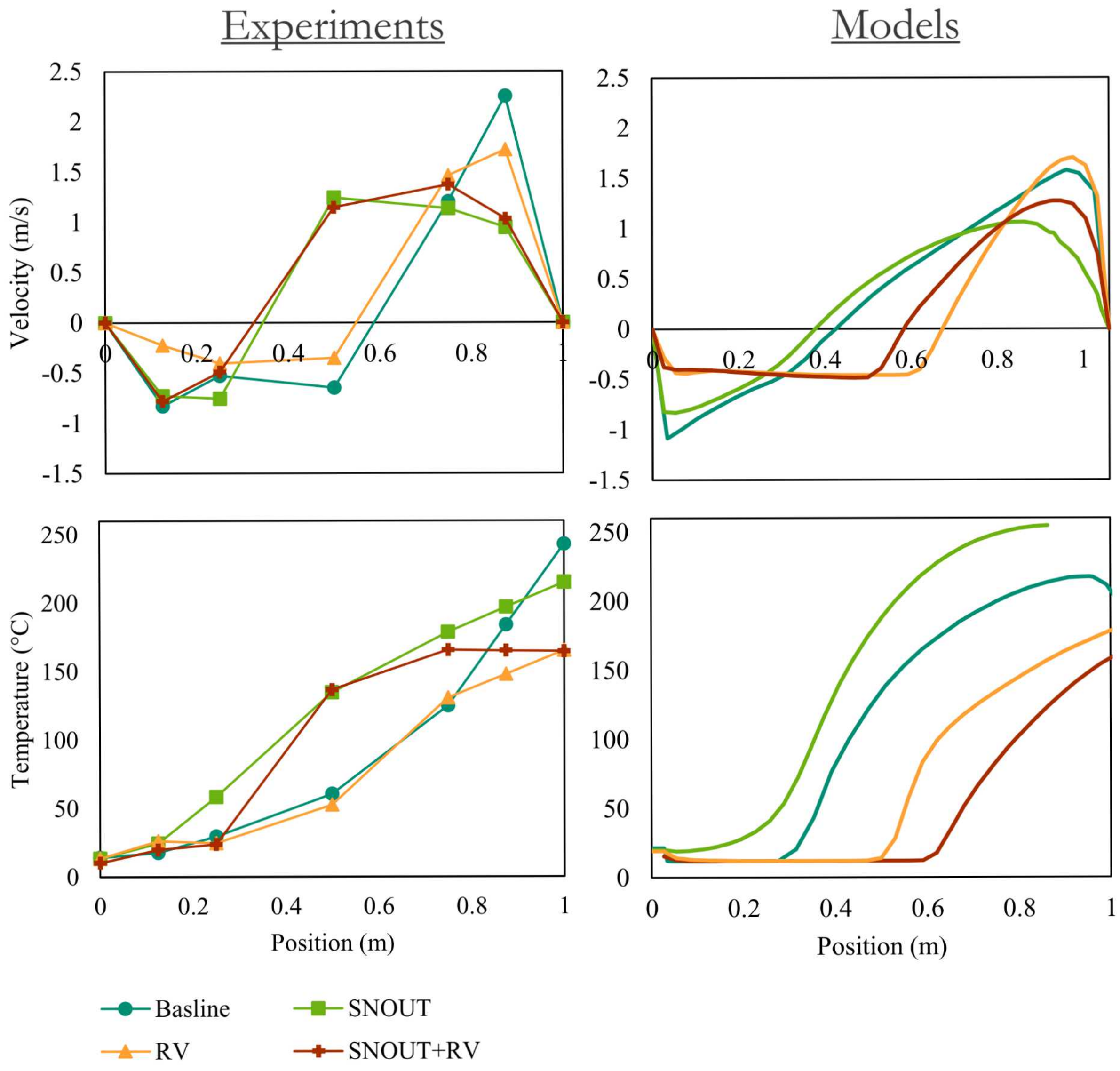
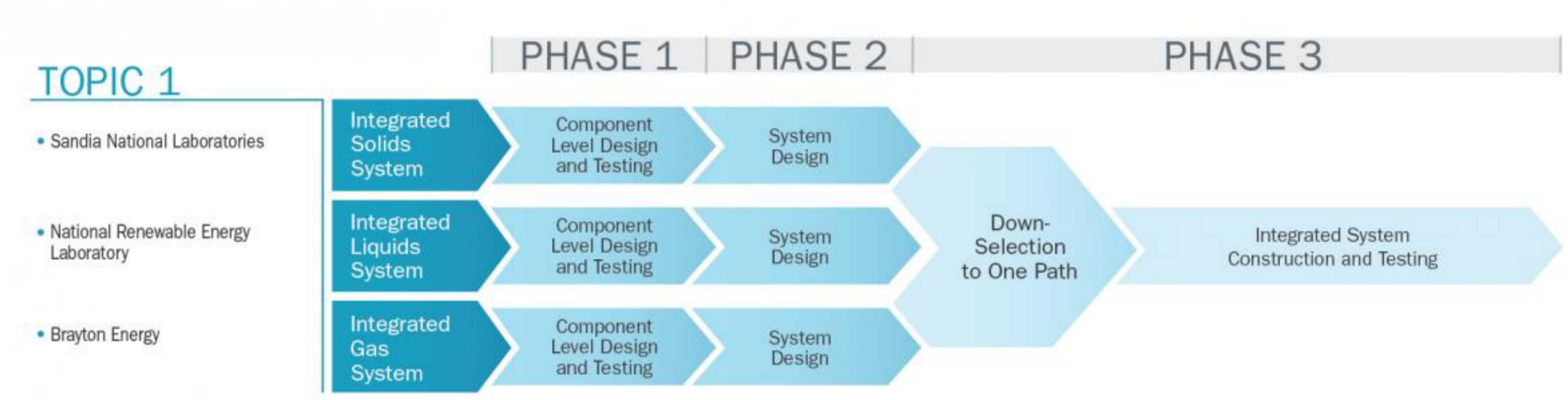




G3P3 outlook

Phase 1 work is nearly completed. Successful de-risked a number of components and features and developed a promising, high efficiency falling particle receiver design.

In the coming months, the plant design will be finalized (Phase 2) and submitted to DOE for evaluation and down-selection. If selected, construction will start early 2021.



This work was funded in part or whole by the U.S. Department of Energy Solar Energy Technologies Office under Award Number 34211
U.S Department of Energy Project Managers: Matthew Bauer, Vijay Rajgopal, and Shane Powers

CST-driven chemical looping

Chemical looping cycles featuring **thermochemical reactions** and other industrial thermochemical processes have the potential to be driven by concentrated solar thermal energy

Chemical looping features multiple sub-reactions which sum to a single desirable chemical reaction, facilitated by solid reactant intermediaries

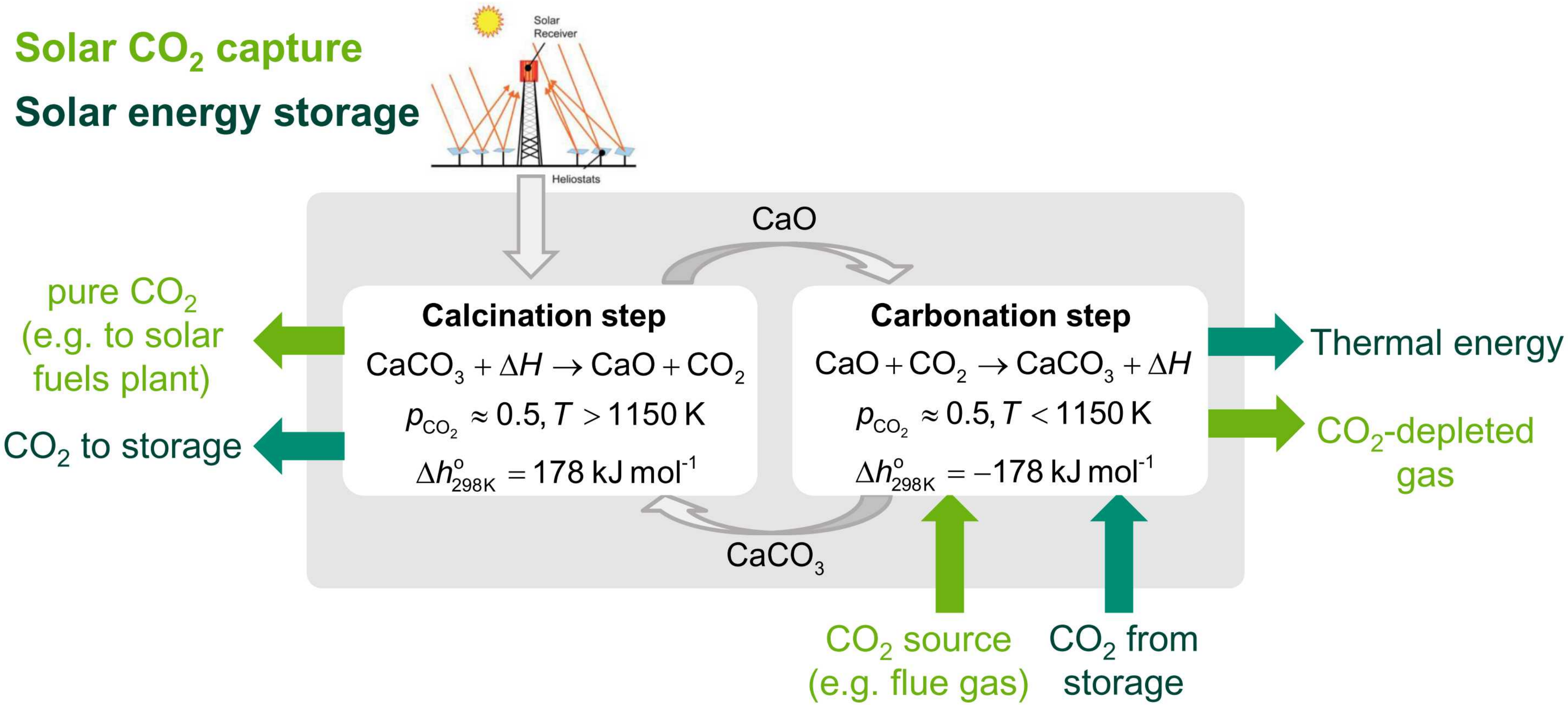
Calcium oxide-based chemical looping cycle is being considered for use with CST for CO_2 capture and TES

Past work: Thermal transport modeling of a particle undergoing calcium oxide chemical looping to guide reactor design/operation and system configuration

Metal oxide/metal carbonate chemical looping

Solar CO_2 capture

Solar energy storage



Net result: a CO_2 containing gas is separated into a CO_2 depleted gas and a concentrated CO_2 stream with a thermal energy input

Net result: thermal energy input and thermal energy output at a later time

Thermal transport modeling

Developed model of single porous reacting particle

Used model to investigate closure models (for gas diffusion in pore space and radiative heat transfer), particle parameters, and operational parameters

Compared model predicted reaction extent to conversion of particles experimentally cycled in TGA

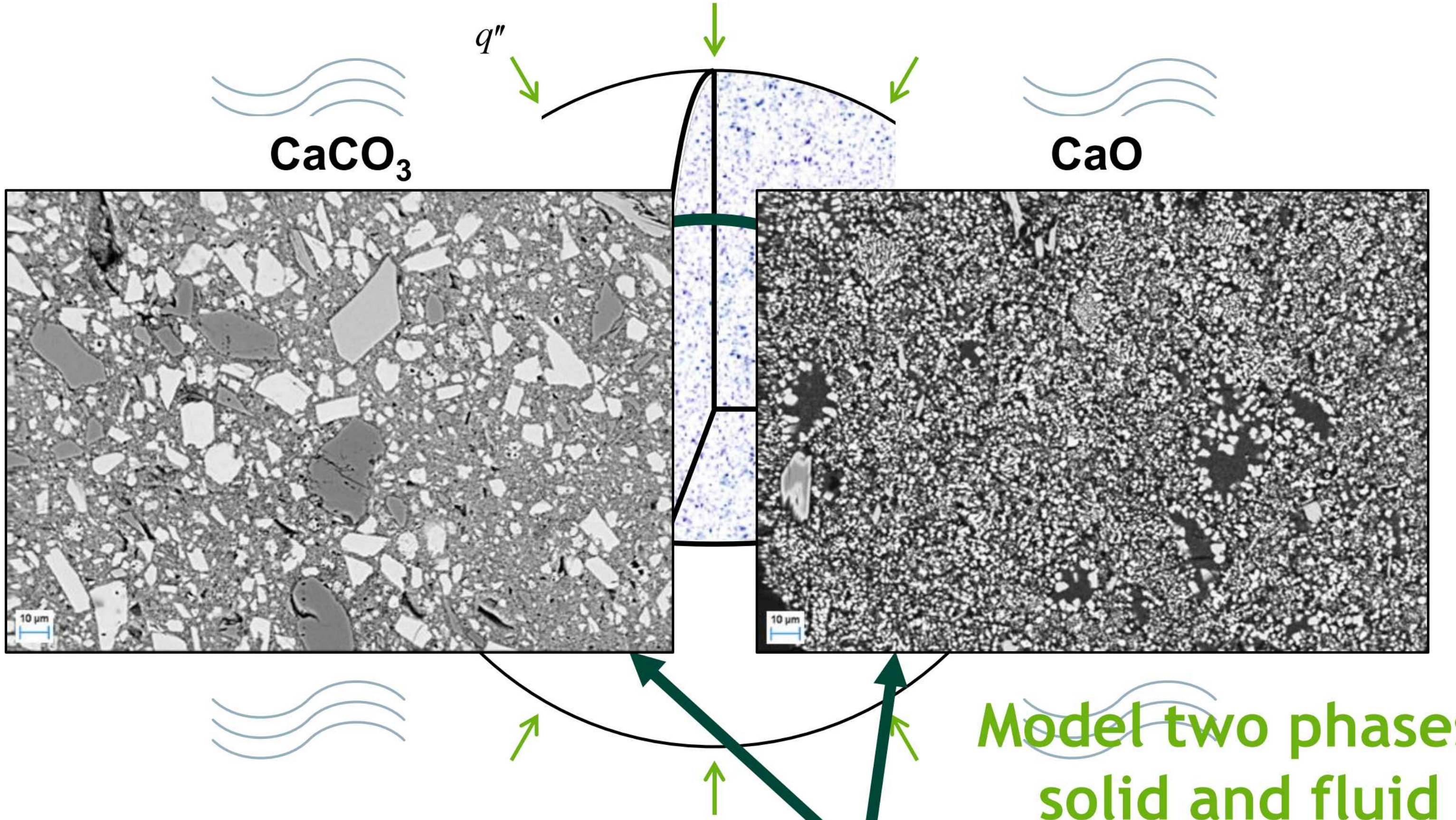
University of Minnesota Driven to Discover®

Australian National University

CSIRO

ARENA Australian Government Australian Renewable Energy Agency

Thermal transport modeling



Model two phases: solid and fluid

The analyzed model system is a single, **porous** particle undergoing **thermochemical cycling** in an idealized, **reactor-like environment**

Thermal transport modeling

5 conservation equations (4 for mass, 1 for energy), 2 constraint equations (Darcy's law and ideal gas equation), and closure equations

Mass transfer

- Chemistry: Volumetric reaction model and reaction rate expression
- Fluid phase: species diffusion and bulk advection

Heat transfer

- Conduction in solid and fluid phases
- Intra-particle radiative heat transfer
- Convection and radiation at the surface

Governing equations are solved numerically using finite volume method and explicit Euler time integration

Thermal transport modeling

Investigations:

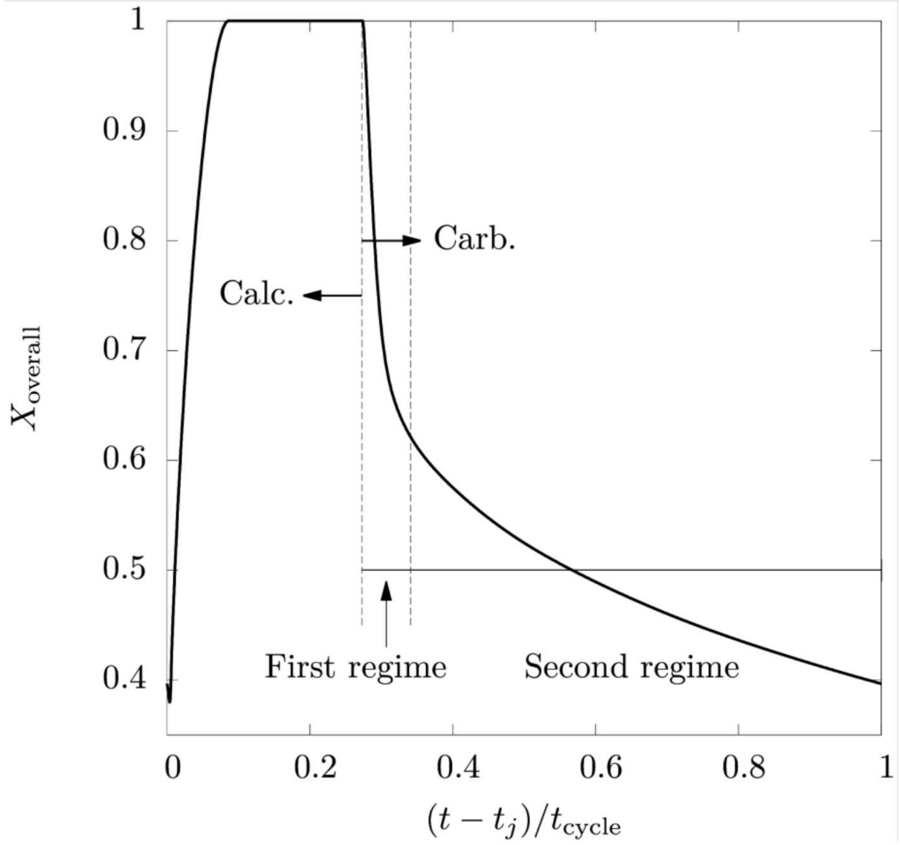
- Different calcination and carbonation **period lengths**
- Calcination and carbonation periods are fixed, while the magnitude of **incident irradiation** on the particle surface, the **particle size**, and the **ambient gas temperature** are varied

To compare cases, non-uniform composition is averaged. Molar extent of $CaCO_3$ calcination ↔ overall conversion ↔ reaction extent

$$X_{local} = 1 - \frac{\bar{\rho}_{CaCO_3}}{\bar{\rho}_{0,CaCO_3}} \qquad X_{overall} = \frac{\int_0^{r_p} 4\pi r^2 X_{local} \mathrm{d}r}{\frac{4}{3}\pi r_p^3} = 1 - \frac{\bar{\rho}_{CaCO_3,overall}}{\bar{\rho}_{0,CaCO_3,overall}}$$

Metrics: sorbent utilization and energetic efficiency

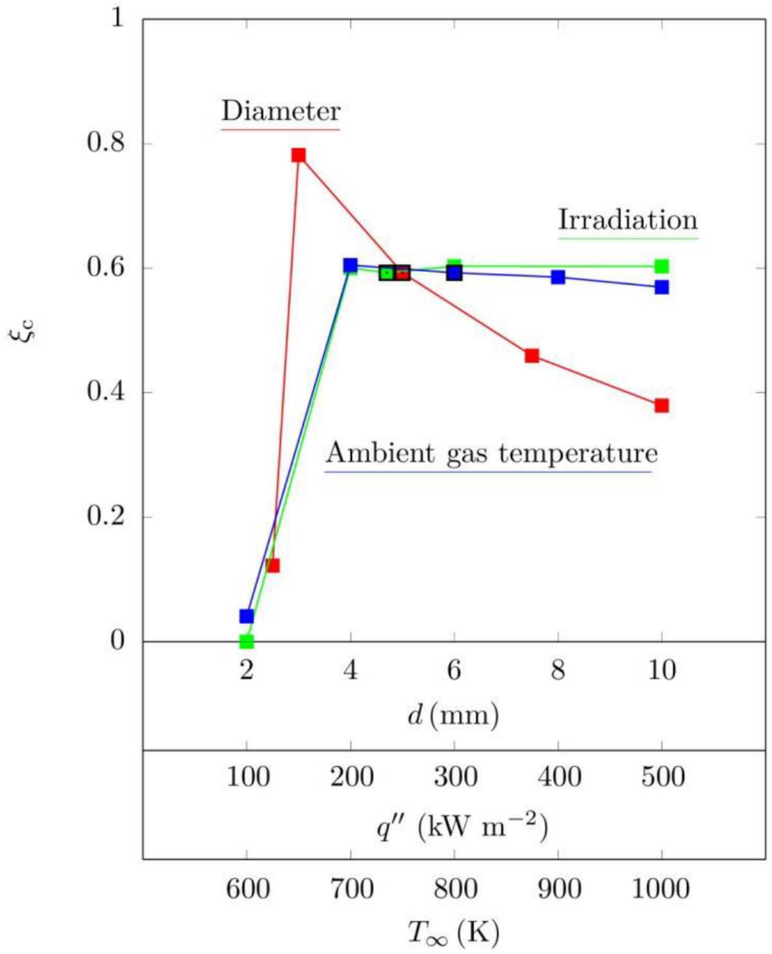
$$\zeta_c = \frac{N_{CO_2,cycle}}{N_{0,CaCO_3,p}} \qquad \eta_e = \frac{N_{CO_2,cycle} \Delta \bar{h}^0_{298\,K}}{Q_{surf,cycle}}, \quad Q_{surf,cycle} = \int_{t_j}^{t_{j+1}} \int_A q''_{surf} \mathrm{d}A \, \mathrm{d}t$$



$0 \le X \le 1$;
100% $CaCO_3$ → $X = 0$;
100% CaO → $X = 1$

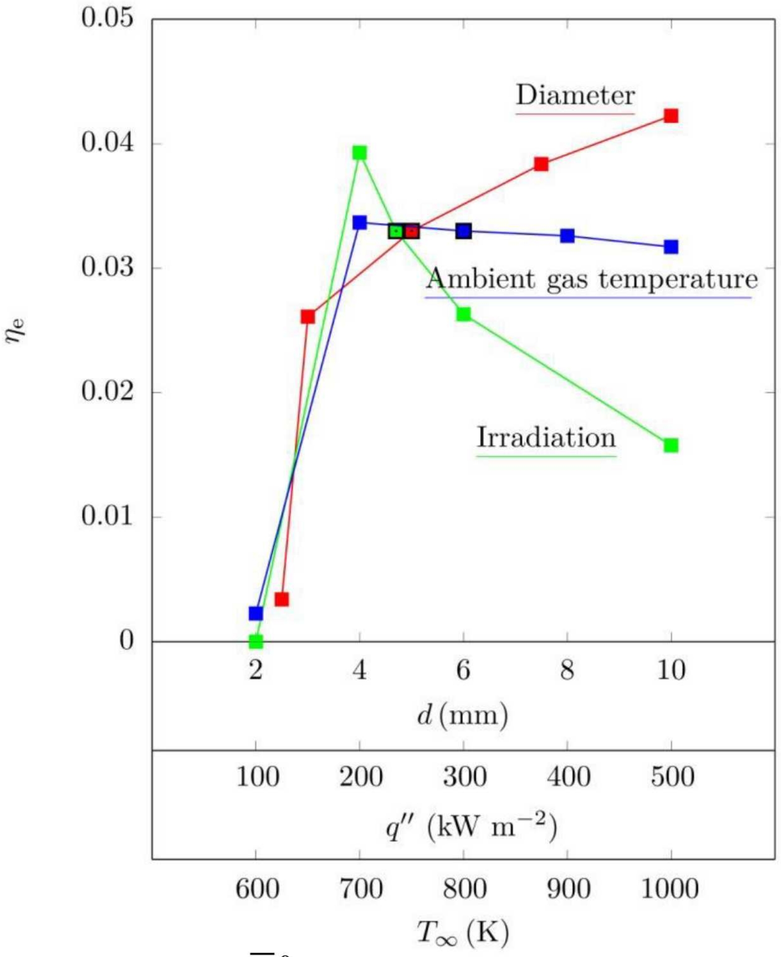
Thermal transport modeling results

Sorbent utilization



$$\bar{\zeta}_c = \frac{N_{CO_2,cycle}}{N_{0,CaCO_3,p}}$$

Energetic efficiency



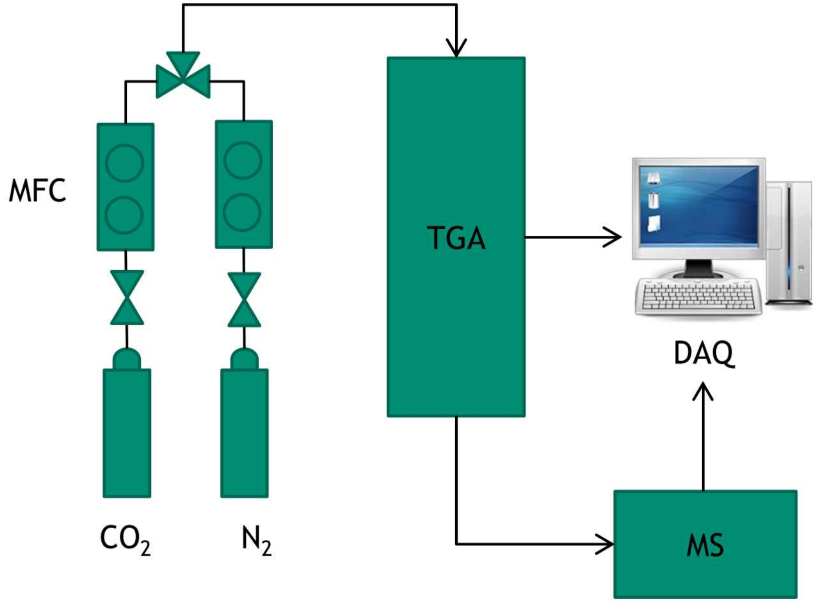
$$\eta_e = \frac{N_{CO_2,cycle}\Delta \bar{h}^0_{298\,K}}{Q_{surf,cycle}}, \quad Q_{surf,cycle} = \int_{t_j}^{t_{j+1}} \int_A q''_{surf} \, dA \, dt$$

Increasing diameter leads to trade off between increased energetic efficiency but decreased sorbent utilization

Increasing irradiation or **gas temperature** does not result in significantly increased in sorbent utilization

Baseline calcination and carbonation period times are **not optimized** for the varied parameters

Comparison to experiments



Single particles of different sizes were thermochemically cycled

20 mL/min flow rate with 3 different CO_2 compositions: 100%, 50%, 25% CO_2 by volume in N_2

Mass change was measured with thermogravimetric analysis

Gas composition was analyzed with mass spectroscopy to confirm mass change was due to calcination and carbonation reactions and not other reactions (e.g. $Ca(OH)_2$ decomposition, impurities, etc.)

Experimental results

Samples are completed calcined → calcination occurs in under 10 minutes

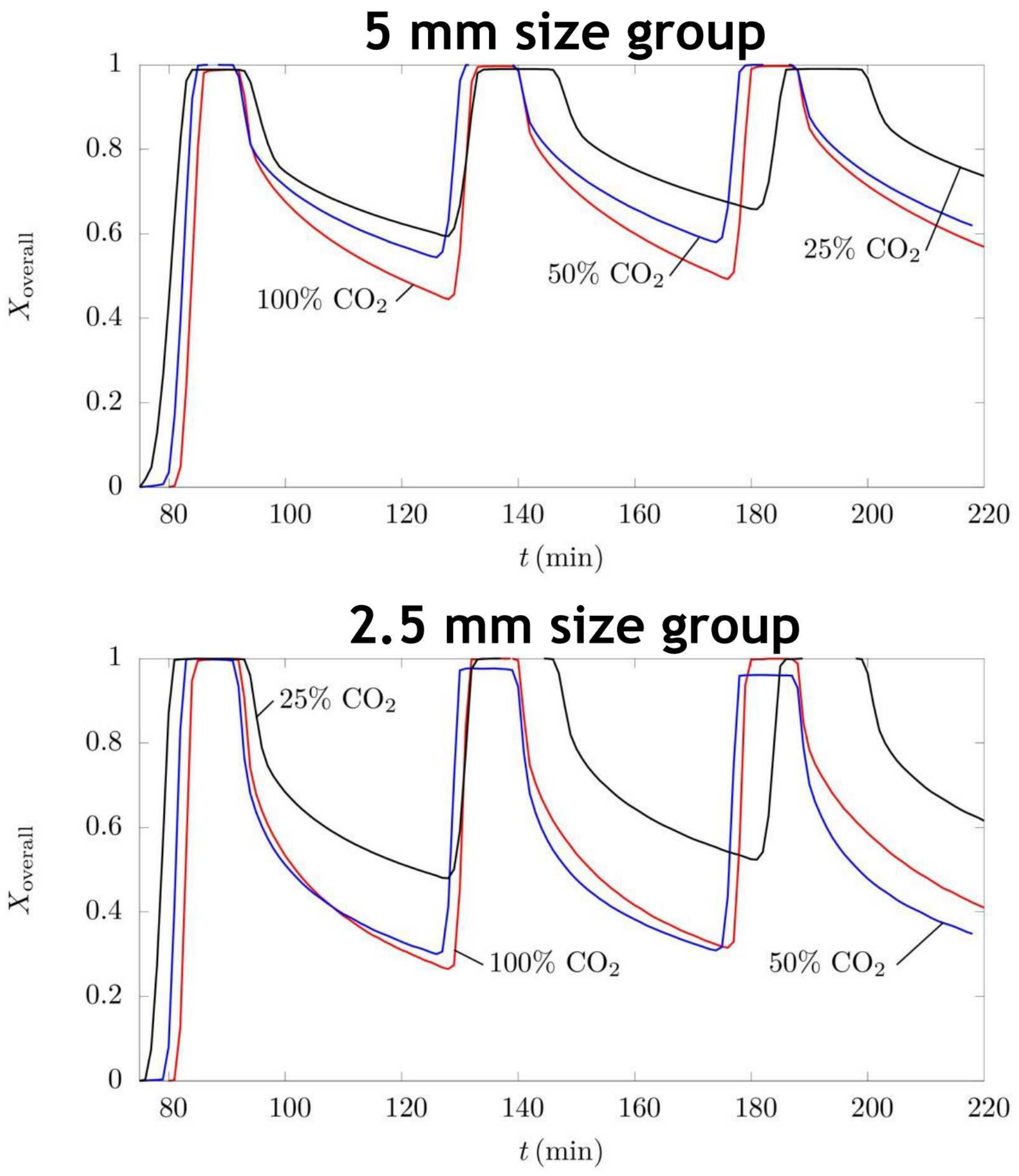
Rapid carbonation is kinetics limited

Slower carbonation is CO_2 diffusion through product layer limited

Carbonation transition dependent on size and CO_2 concentration

Critical product layer thickness 0.05 to 2 mm depending on ambient CO_2 concentration

SEM–BSE images of sphere cross sections show porous inner region and dense outer region



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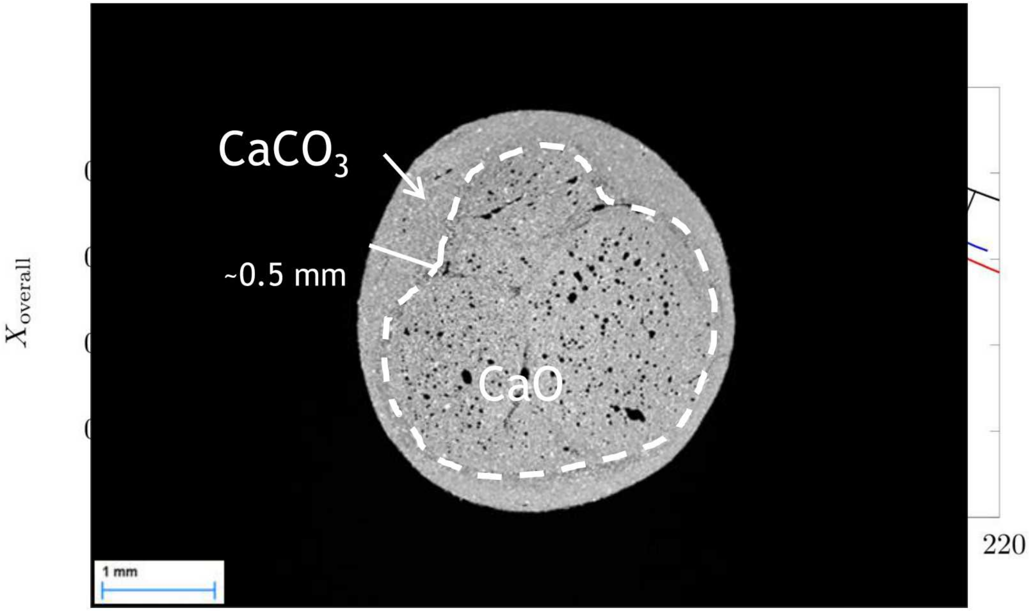
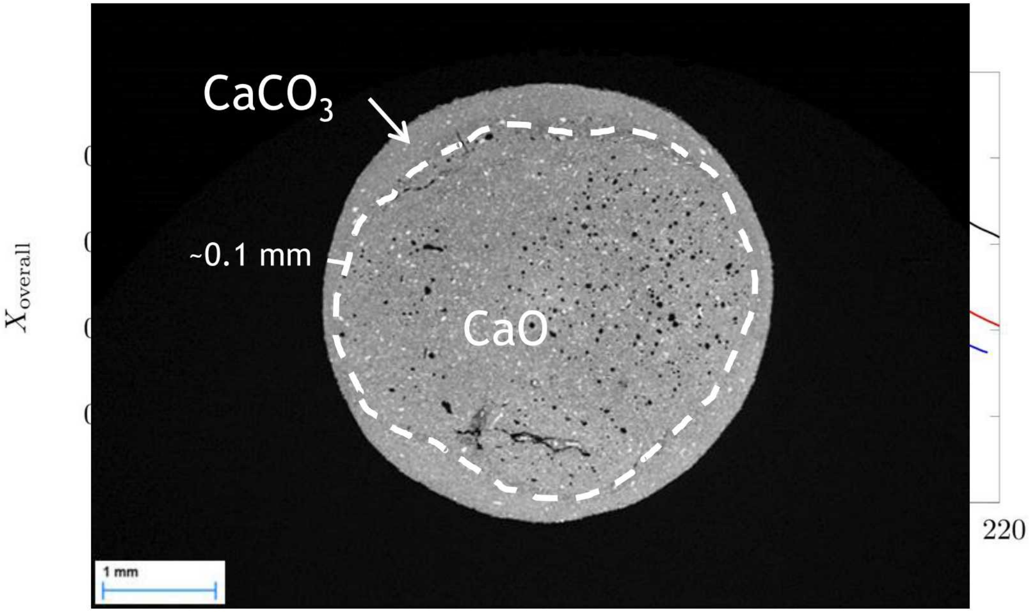




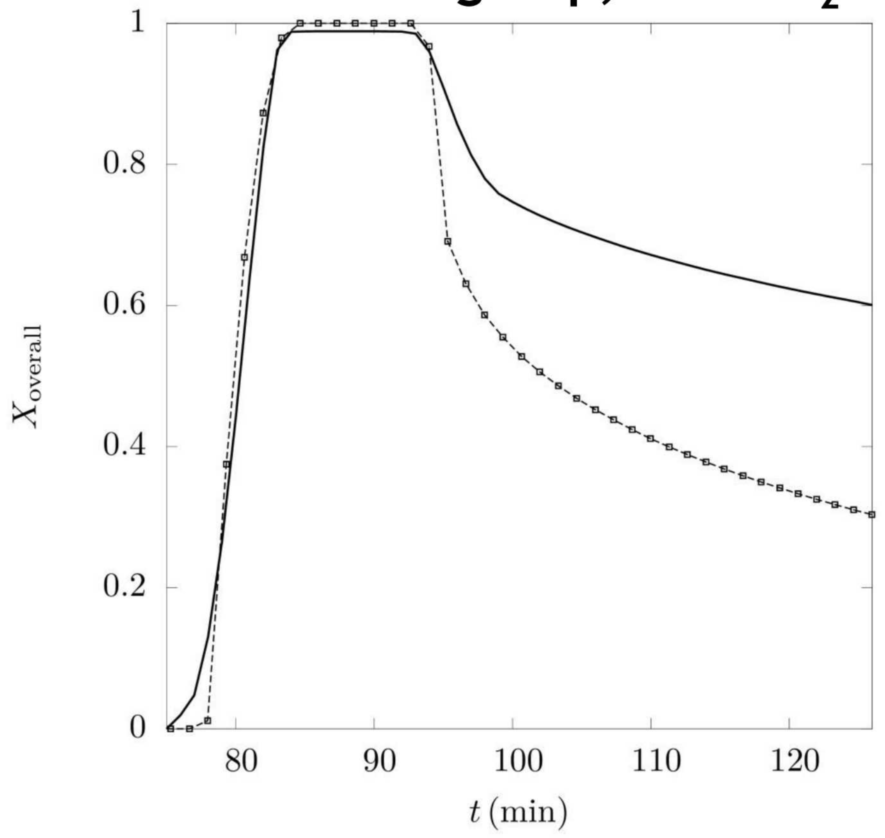
Comparison to experiments

TGA conditions chosen to match model as closely as possible → Model boundary conditions modified to compensate for TGA limitations

Disagreement between results using original model with modified boundary conditions and experiments motivates further adjustments

Carbonation reaction specific surface area and **effective diffusivity model**

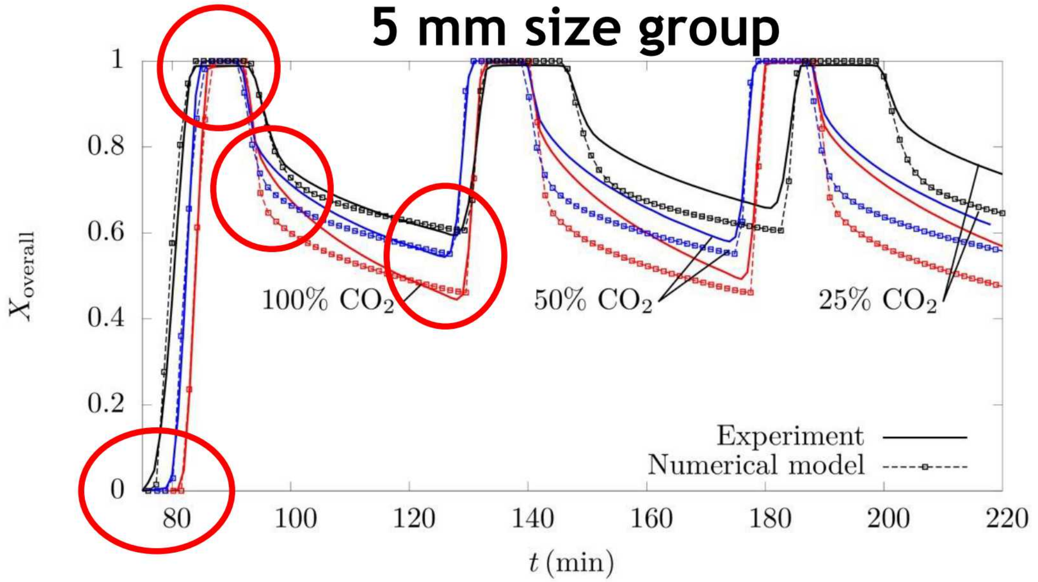
5 mm size group, 25% CO_2



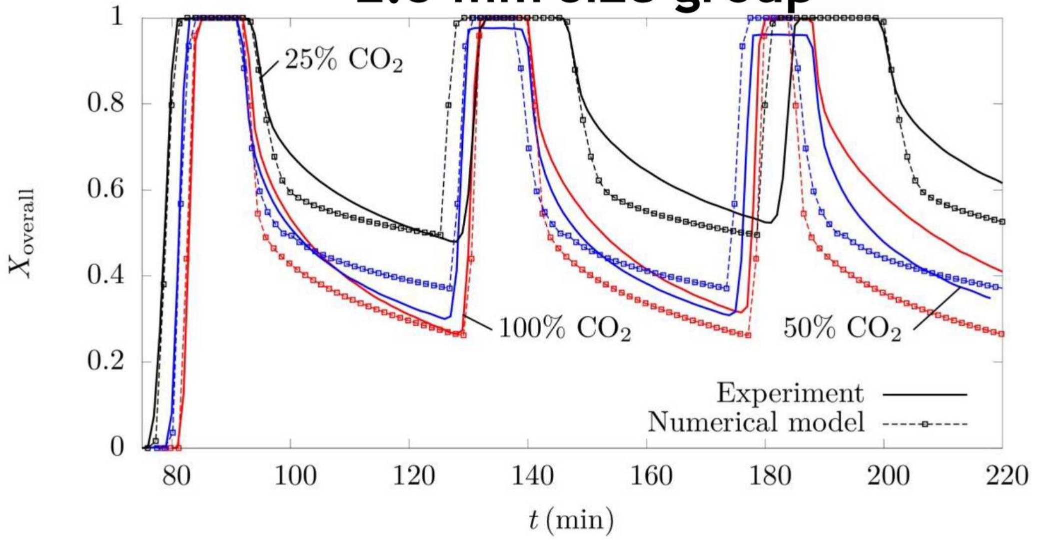
Comparison to experiments

- Numerical results match first cycle of experimental results but not subsequent cycles
- Transitions in numerical results are sharper than experimental results → numerical mesh may not be fine enough to predict subtle transitions

5 mm size group



2.5 mm size group



CST-driven chemical looping outlook

Prototype solar thermochemical reactor at the ANU for studying CaO-based chemical looping cycle

Thermochemical reactions are everywhere in chemical processing and commodity production industries

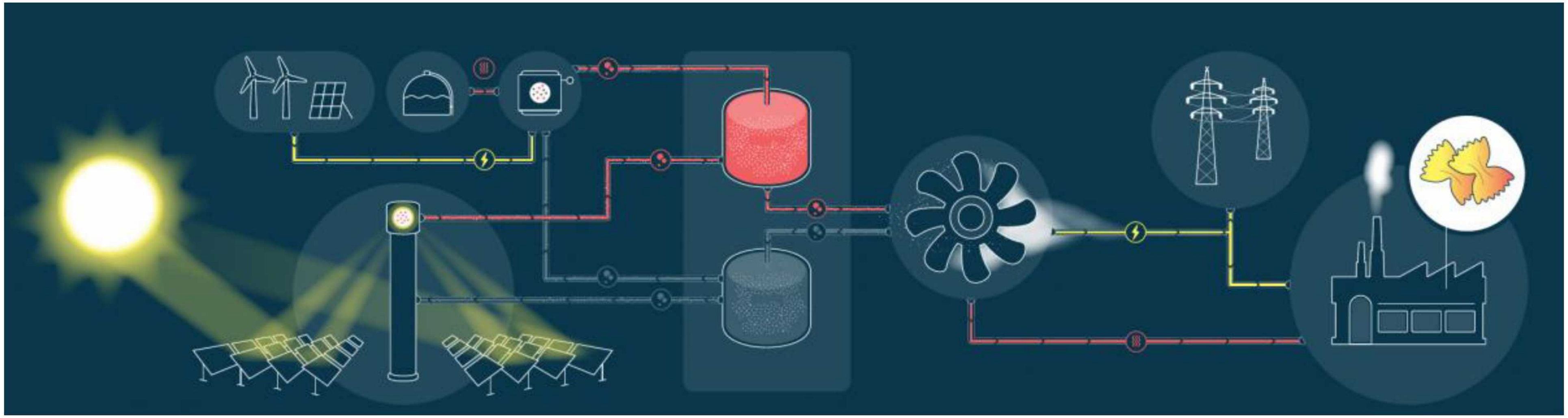
Many require high temperature process heat → potential application for concentrated solar thermal technologies that other renewable energy technologies cannot currently meet

Chemical looping with conventional sources of process heat has been realized on the pilot plant scale, maturing technology

Next step for realization of CST-driven chemical looping is to couple CST and chemical looping together

Future research

- Modeling of seasonal mid- and low-temperature thermal energy storage (NSF Faculty Early Career Development, L'Oréal USA For Women in Science fellowship)
- System and technoeconomic analysis of integrating solar thermal energy into industrial processes (US DOE, partner with industry)



hiflex-project.eu

Seasonal thermal energy storage modeling

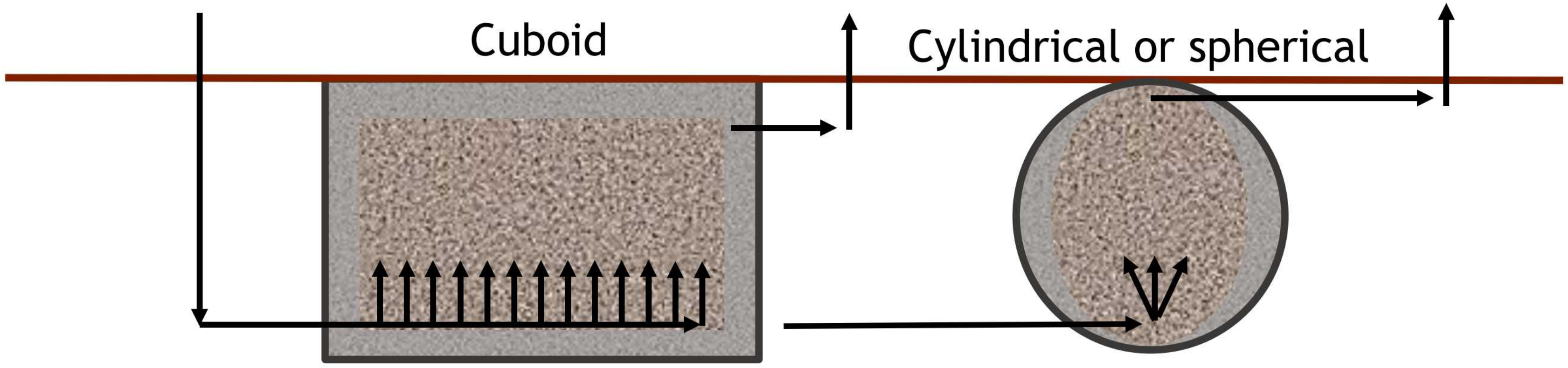
Solar collector:

- Non-concentrating tubular (lower temperature)
- Concentrating collector (higher temperature)

HTF:

- Air
- Water
- Thermal oil

Tank geometry:



Storage media:

- Inert particles (sensible TES)
- Reacting particles (sensible+thermochemical TES)

Seasonal thermal energy storage modeling

Two modeling approaches:

- Transient modeling of thermal gradients and reaction extent within storage tank while in charging and discharging modes to inform tank design, tolerable losses, and compatible HTF temperatures and thermochemical systems
- Lumped capacitance transient modeling of seasonal charging and discharging of storage tank to estimate seasonal losses and round trip efficiency

Application scale: sizing system based on heating load (greenhouse or residence, hospital or office building) and system efficiency

Teaching and supervising experience

University of Minnesota

- Manufacturing lab teaching assistant (lab size ~8–10 students)
- Heat transfer teaching assistant (tutorial size ~40 students)
- Student-athlete tutor (1-on-1 tutoring in various subjects)

ANU

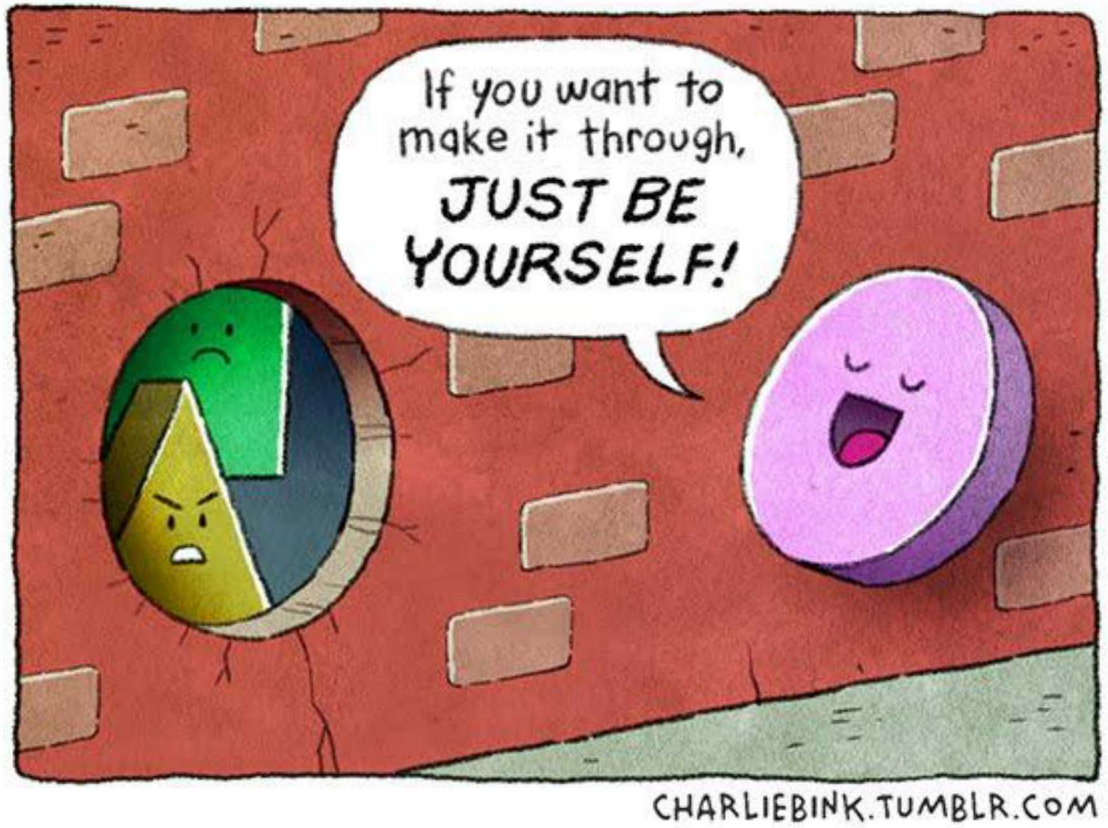
- Tutor for mechanics (tutorial size ~20)
- Tutor and guest lecturer for thermodynamics (tutorial size ~20, class size ~100 students) and energy systems engineering (lab size ~6–8 students, class size ~ 100 students)
- Guest lecturer
- Received an award for Excellence in Education for tutoring energy systems engineering
- Associate supervisor to undergraduate honours student

Sandia

- Supervisor to graduate student intern

Teaching philosophy

- I believe:
  - Systemic inequalities affect students' interest in engineering and abilities to excel
  - Intersectionality of marginalized identities compounds systemic inequalities
  - Diversity is not a 0 or 1 answer (I have identities that are marginalized in certain contexts; and I have identities that are privileged in certain contexts.)
- Teaching philosophy:
  - Quality course delivery (content, engagement, and interaction) and research
  - Advocate for and support diversity in research and teaching because diverse teams will produce better results toward achieve diverse energy technology goals



Potential to contribute at UMass Lowell

Diversity and inclusion work

- Incorporating diversity into course curricula where possible and appropriate
- Mentoring women and students of color
- Using the privileged identities I have to boost voices of others with less privilege

Work to 'rebrand' (or 'brand') engineering

- Away from: non-inclusive, stereotypical, and/or inaccurate examples of mechanical/aerospace engineers in Hollywood (National Treasure, Iron Man, The Big Bang Theory)
- Towards: diverse people **working in teams**, **being creative**, and **traveling**, who use science to address major societal issues

Potential to contribute at UMass Lowell

High level of professionalism and technical competency

Passion for working on hard societal problems (technical and social) and diverse solutions

I don't explicitly identify as a person of color and have a lot of privilege, I do have marginalized identities and bring a unique cultural and professional background to most environments I work in.

Bensheim, Germany

Great Barrier Reef, Town of 1770, Australia

Thank you

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