SAND2018-6931C

Evaluation of Alternative Designs for a High-Temperature Particle-to-sCO2 Heat Exchanger

Clifford K. Ho,[1] Matthew Carlson,[1]
Kevin J. Albrecht,[1] Zhiwen Ma,[2]
Sheldon Jeter,[3] Clayton M. Nguyen[3]

[1]Sandia National Laboratories
[2]National Renewable Energy Laboratory
[3]Georgia Institute of Technology

SAND2018-

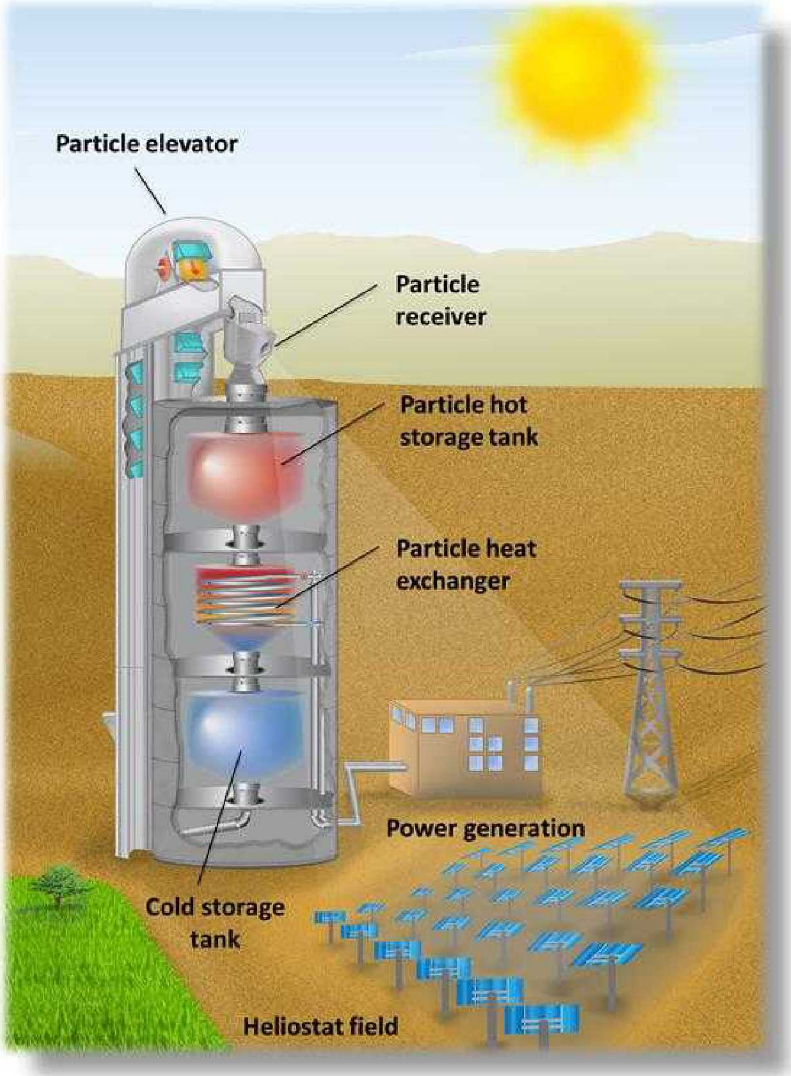
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Outline

- Introduction and Objectives
- Heat Exchanger Design Criteria
- Analytical Hierarchy Design Selection Process
- Final Design

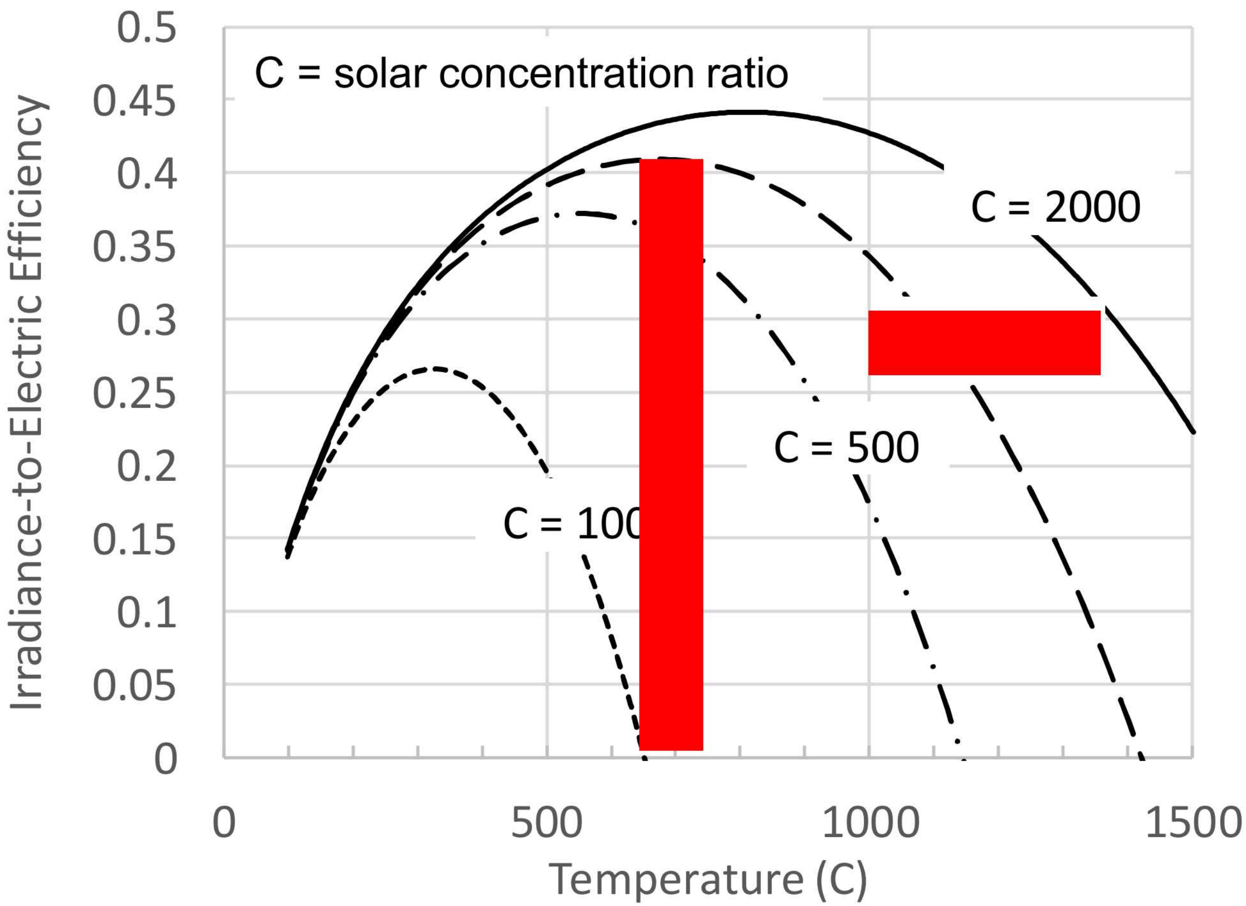
Introduction

- Next-generation supercritical CO_2 (sCO2) Brayton power cycles are being pursued
  - >50% thermal-to-electric efficiency
  - Need sCO2 ≥ 700 ˚C at ≥20 MPa
- Would like renewable energy heat source for sCO2 cycle
  - Current state-of-the-art CSP cannot meet high temperatures; molten nitrate salt decomposes at ~600 °C
  - Use solid particles as heat-transfer and storage medium



CSP and sCO2 Brayton Cycle

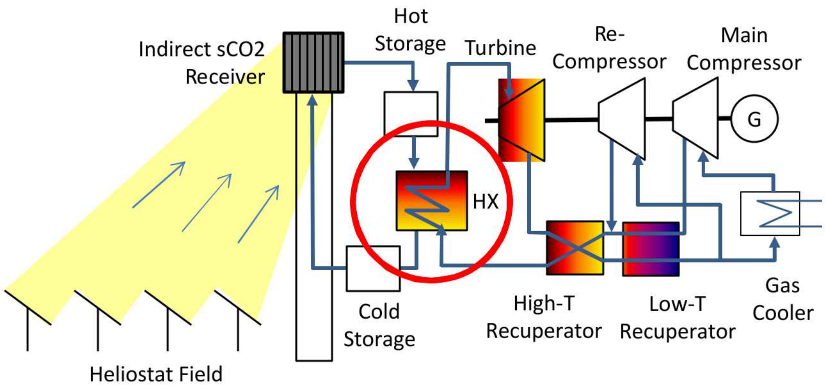
"A Good Match"



At a solar concentration ratio of ~1000, ideal temperature for CSP system matches desired turbine inlet temperature for sCO2 cycle (~700 °C)

Problem Statement

- Particle-to-sCO2 heat exchangers do not exist
  - sCO2 ≥ 700 °C at ≥ 20 MPa
- Challenges
  - Particle-side heat transfer
  - Thermomechanical stresses
  - Materials
    - High operating temperatures and pressures
    - Erosion
  - Costs



Solarized sCO2 recompression Brayton cycle

www.solexthermal.com

Objectives

- Evaluate alternative particle heat exchanger designs that can heat sCO_2 to 700 °C at 20 MPa for 100 kW prototype
  - Define design criteria
  - Use quantitative Analytical Hierarchy Process
  - Construct and integrate final design with Sandia's falling particle system

Heat Exchanger	Advantages	Disadvantages
Fluidized Bed	High heat-transfer coefficients	Energy and mass loss from fluidization
Moving packed bed (shell/tube)	Gravity-fed particle flow; low erosion	Low particle-side heat transfer
Moving packed bed (shell/plate)	High potential surface area for particle contact; low erosion	Requires diffusion-bonding of plates

Outline

- Introduction and Objectives
- Heat Exchanger Design Criteria
- Analytical Hierarchy Design Selection Process
- Final Design

Design Criteria

Design Criteria	Notes
Cost	Want low cost of prototype and larger scale systems (< \$150/kW_t)
Heat Transfer Coefficient	Want large overall heat transfer coefficient (>100 W/m^2-K)
Structural Reliability	Want maximum allowable working pressure > 20 MPa at minimum design metal temperature of 750 C; long-term reliability
Manufacturability	Want ease of manufacturing and demonstrated ability to build
Parasitics & Heat Losses	Want low power requirements, pressure drop, and heat losses
Scalability	Need to be able to scale up to ~20 MW_t thermal duty
Compatibility	Can be readily integrated with particle receiver and sCO2 flow loop
Erosion & Corrosion	Want to minimize thinning of walls and tubes from particle and sCO2 flow; need to ensure 30 year lifetime
Transient Operation	Want to minimize transient start-up and impact of thermal stresses
Inspection Ease	Want ability to inspect internals of the heat exchanger to evaluate corrosion, erosion, fatigue, etc.

Outline

- Introduction and Objectives
- Heat Exchanger Design Criteria
- Analytical Hierarchy Design Selection Process
- Final Design

Analytical Hierarchy Process

1. Identify a goal
2. Identify criteria to achieve goal and weight criteria
3. Define alternative designs or options to achieve goal
4. For each criterion, perform pairwise comparison of each design option
5. Obtain a final score for each design option

A team of researchers and heat-exchanger vendors independently assigned ratings to each pair of criteria and to each pair of design options

Pairwise Ratings of Design Criteria

Criteria Ratings	Cost	Heat Transfer Coefficient	Structural Reliability	Manufacturability	Parasitics & Heat Losses	Scalability	Compatibility	Erosion & Corrosion	Transient Operation	Inspection Ease
Cost	1.00	0.50	0.50	1.00	3.00	1.00	2.00	2.00	3.00	5.00
Heat Transfer Coefficient	2.00	1.00	1.00	2.00	2.00	2.00	3.00	2.00	3.00	5.00
Structural Reliability	2.00	1.00	1.00	2.00	2.00	1.00	2.00	1.00	2.00	4.00
Manufacturability	1.00	0.50	0.50	1.00	1.00	1.00	2.00	1.00	2.00	4.00
Parasitics & Heat Losses	0.33	0.50	0.50	1.00	1.00	2.00	2.00	1.00	2.00	4.00
Scalability	1.00	0.50	1.00	1.00	0.50	1.00	1.00	2.00	2.00	4.00
Compatibility	0.50	0.33	0.50	0.50	0.50	1.00	1.00	0.50	2.00	3.00
Erosion & Corrosion	0.50	0.50	1.00	1.00	1.00	0.50	2.00	1.00	2.00	4.00
Transient Operation	0.33	0.33	0.50	0.50	0.50	0.50	0.50	0.50	1.00	3.00
Inspection Ease	0.20	0.20	0.25	0.25	0.25	0.25	0.33	0.25	0.33	1.00

Pairwise Ratings of Design Criteria and Options

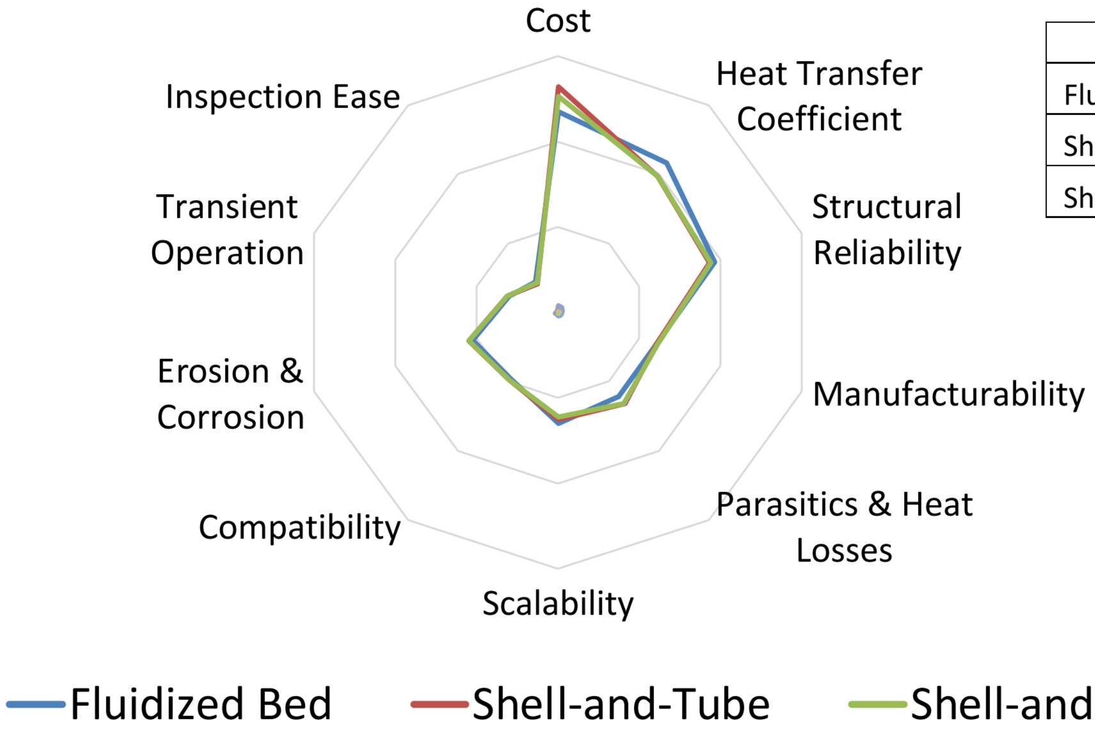
Criteria Weightings
= 1/5 (or 0.2): Extremely worse (less important)
= 1/4 (or 0.25): Significantly worse (less important)
= 1/3: Moderately worse (less important)
= 1/2 (or 0.5): Slightly worse (less important)
= 1: Equal (equally important)
= 2: Slightly better (more important)
= 3: Moderately better (more important)
= 4: Significantly better (more important)
= 5: Extremely better (more important)

Final Criteria Weightings

Criteria	Weight
Cost	0.19
Heat Transfer Coefficient	0.15
Structural Reliability	0.14
Manufacturability	0.09
Parasitics & Heat Losses	0.10
Scalability	0.09
Compatibility	0.07
Erosion & Corrosion	0.08
Transient Operation	0.05
Inspection Ease	0.03

Final weighted scores for each design

Final Scores	Cost	Heat Transfer Coefficient	Structural Reliability	Manufactur-ability	Parasitics & Heat Losses	Scalability	Compatibility	Erosion & Corrosion	Transient Operation	Inspection Ease
Fluidized Bed	0.2495	0.2817	0.2702	0.2634	0.2509	0.2732	0.2616	0.2577	0.2599	0.2780
Shell-and-Tube	0.2806	0.2574	0.2615	0.2639	0.2748	0.2632	0.2666	0.2683	0.2676	0.2577
Shell-and-Plate	0.2693	0.2579	0.2633	0.2673	0.2731	0.2591	0.2666	0.2697	0.2676	0.2607



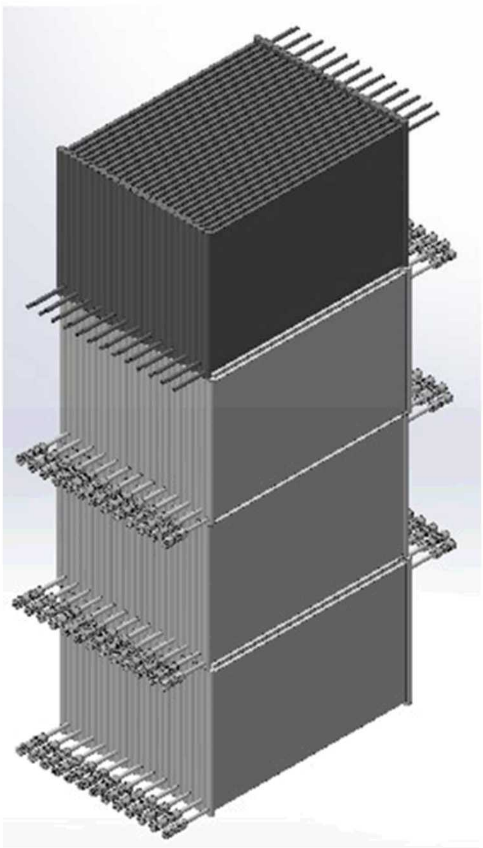
Design	Final Weighted Score
Fluidized Bed	0.2219
Shell-and-Tube	0.2245
Shell-and-Plate	0.2225

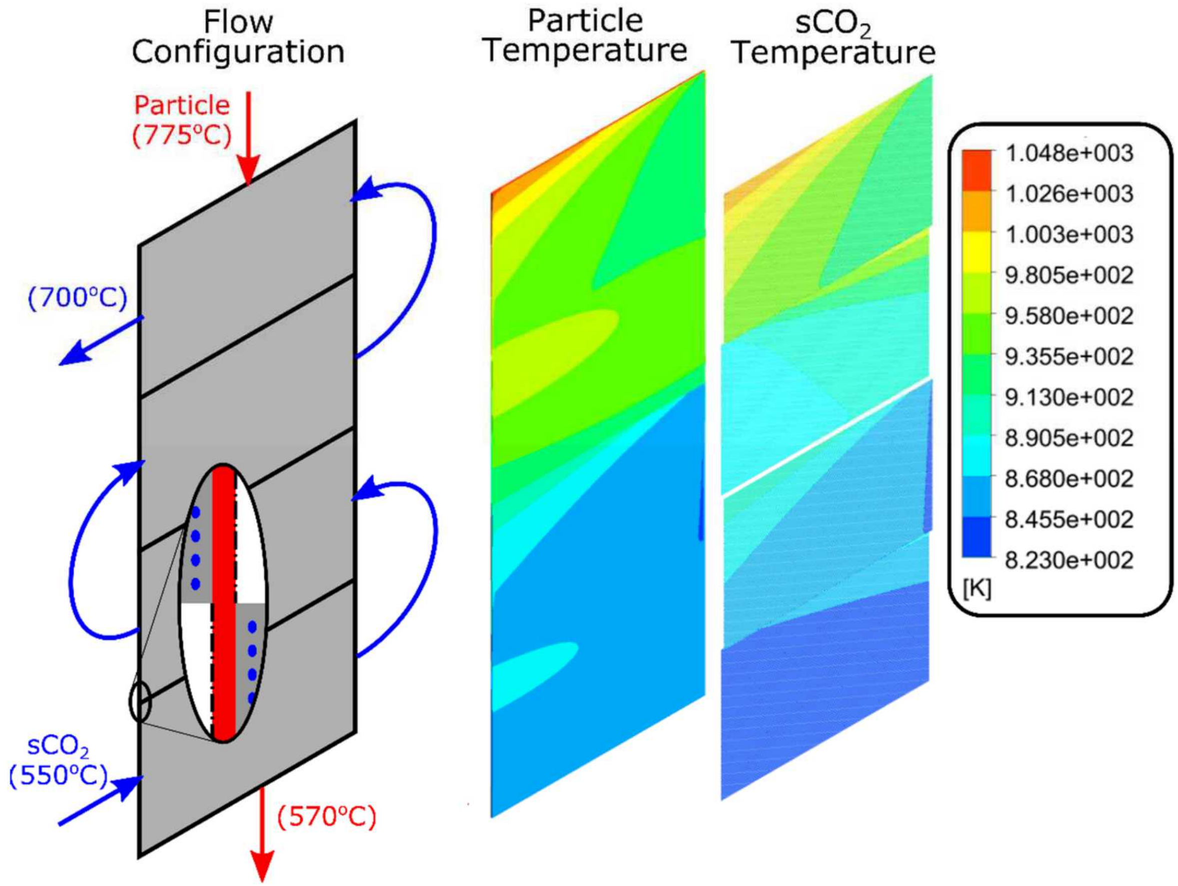
Shell-and-plate was selected for final design and procurement

Outline

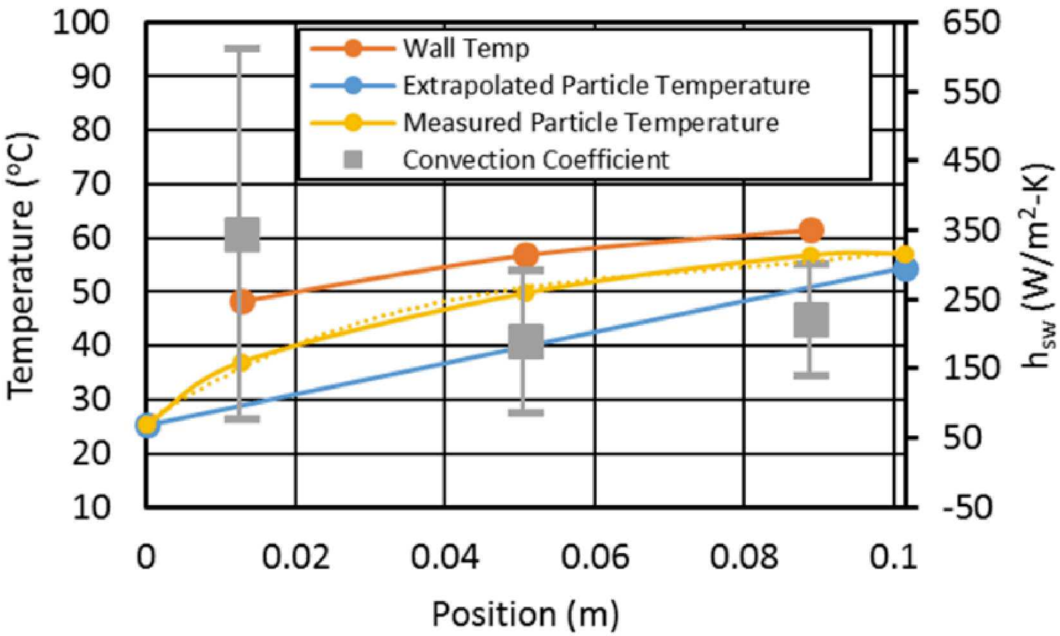
- Introduction and Objectives
- Heat Exchanger Design Criteria
- Analytical Hierarchy Design Selection Process
- Final Design

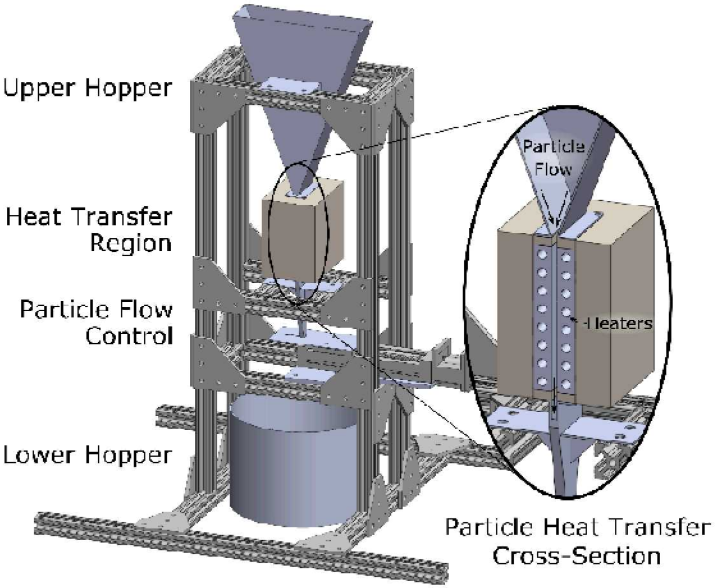
Shell-and-Plate Final Design





Measured performance of bench-scale system



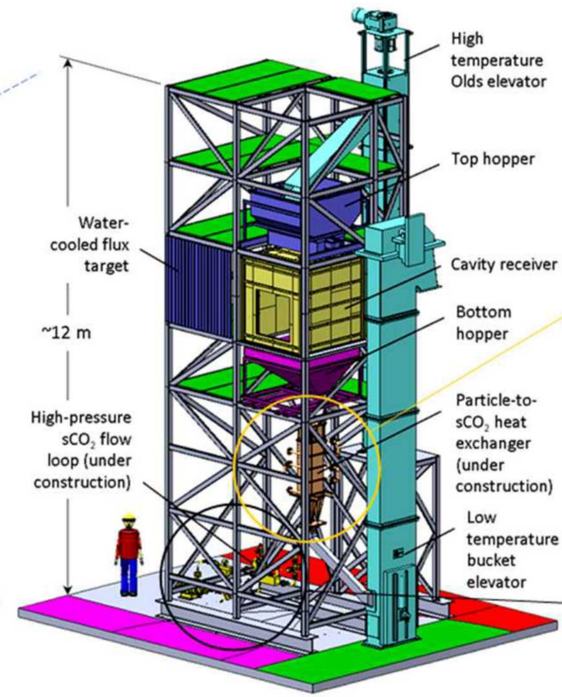


Albrecht and Ho (2017)

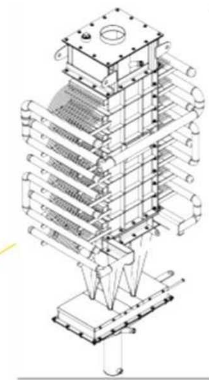
Measured particle/wall heat transfer coefficients ~200 W/m^2-K

Integrated System

Particle receiver testing at the National Solar Thermal Test Facility at Sandia National Laboratories, Albuquerque, NM

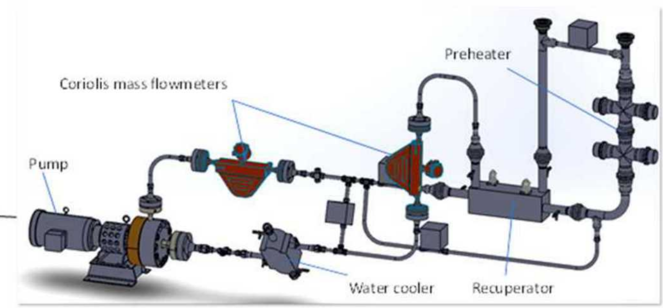


High-Temperature Particle Receiver



Solex/VPE particle/sCO2 shell-and-plate heat exchanger

- Heat duty = 100 kW
- $T_{particle,in}$ = 775 °C
- $T_{particle,out}$ = 570 °C
- $T_{sCO2,in}$ = 550 °C
- $T_{sCO2,out}$ = 700 °C
- $\dot{m}$ = 0.5 kg/s



sCO_2 flow system provides pressurized sCO_2 at 550 °C to heat exchanger for test and evaluation

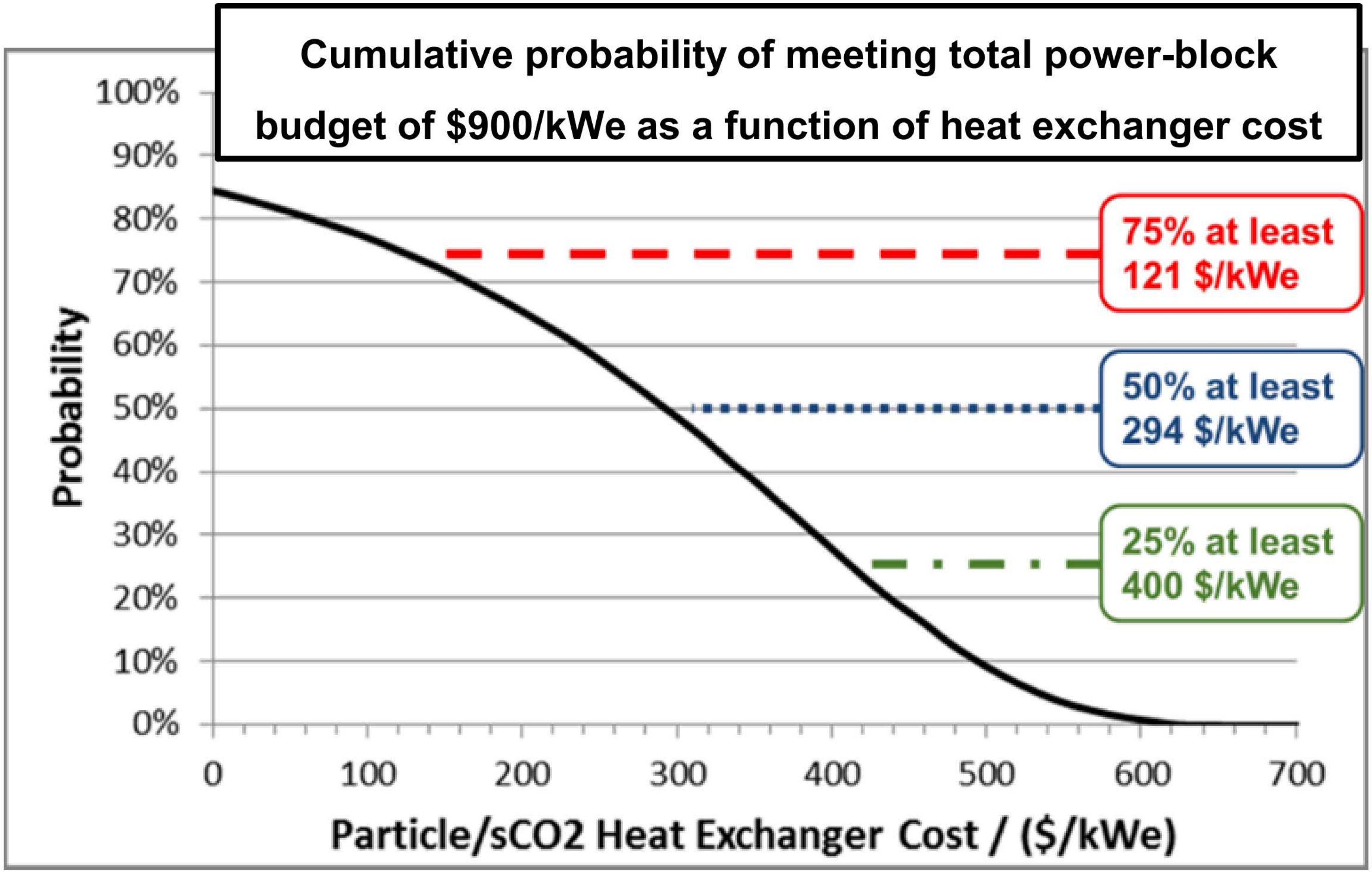
Summary

- Analytical Hierarchy Process was used to quantitatively evaluate alternative particle-to-sCO2 heat exchangers
  - Fluidized bed
  - Shell-and-tube moving packed bed
  - Shell-and-plate moving packed bed
- Design criteria were defined and pairwise ratings were performed for each criteria and design option
- The shell-and-plate design was selected and is being procured for integration with Sandia's particle test loop and sCO2 flow system

Questions?

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

Cost Criterion



50% probability of meeting total power block cost with heat exchanger cost of ~\$300/kW_e or ~\$150/kW_t