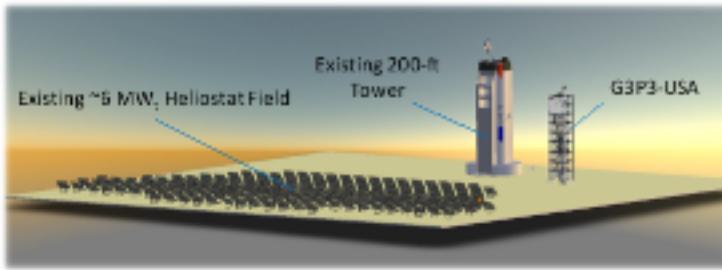




Evaluation of Particle-to-sCO₂ Heat Exchangers and On-Sun Testing



PRESENTED BY

Clifford K. Ho

Sandia National Laboratories, Albuquerque, NM, ckho@sandia.gov

Contributors:

SNL (K. Albrecht, M. Carlson, H. Laubscher, F. Alvarez), Solex, VPE, Babcock & Wilcox, National Renewable Energy Laboratory, Georgia Tech



Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & 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.

Objectives



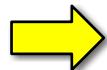
- Evaluate alternative particle heat exchanger designs that can heat sCO₂ to 700 °C at 20 MPa for 100 kW prototype
 - Define design criteria
 - Use quantitative Analytical Hierarchy Process
 - Construct and integrate final design with Sandia's falling particle system

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

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

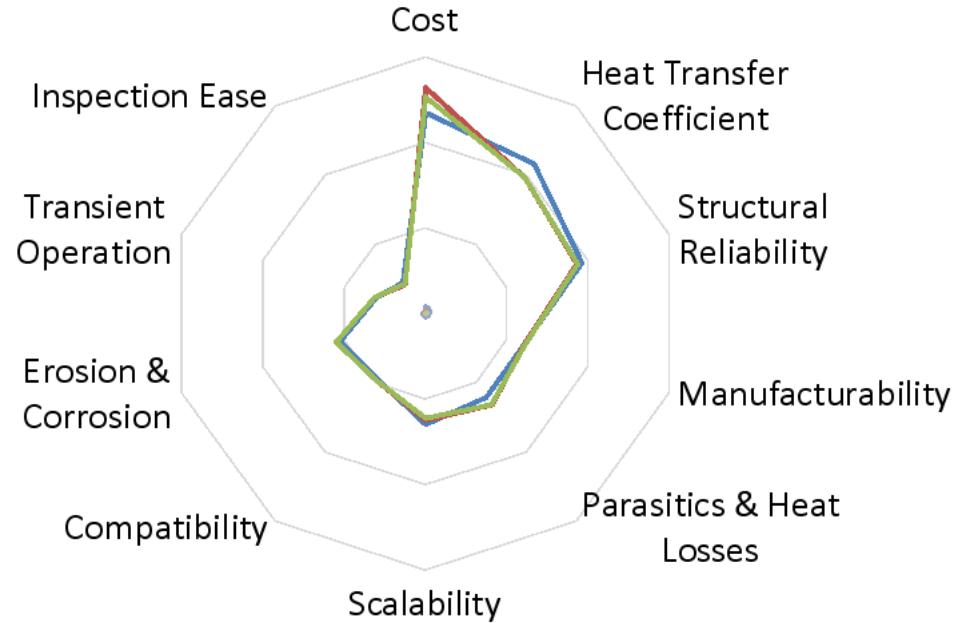
Final Criteria Weightings

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

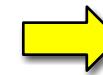
Final weighted scores for each design



Final Scores	Cost	Heat Transfer Coefficient	Structural Reliability	Manufacturability	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

— Fluidized Bed

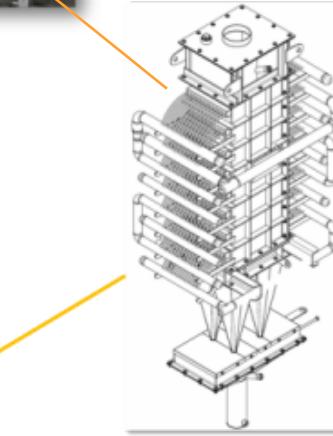
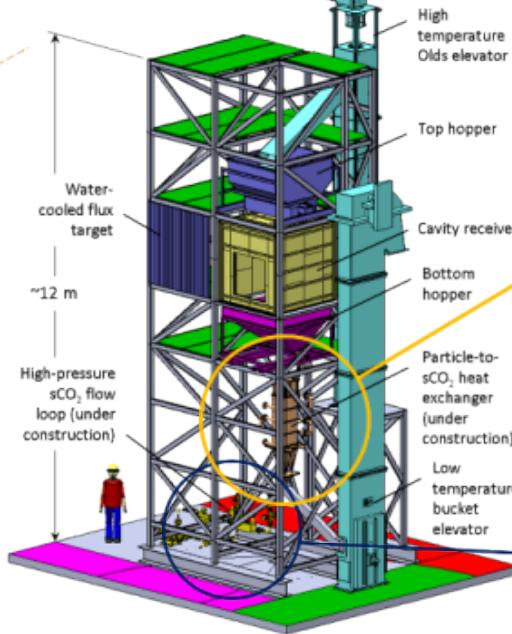
— Shell-and-Tube

— Shell-and-Plate

Integrated Shell-and-Plate Particle-to-sCO₂ System

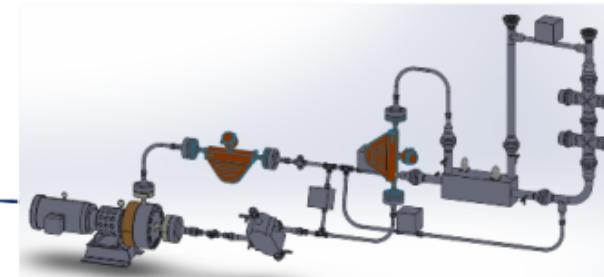


Particle receiver testing at the National Solar Thermal Test Facility at Sandia National Laboratories, Albuquerque, NM



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

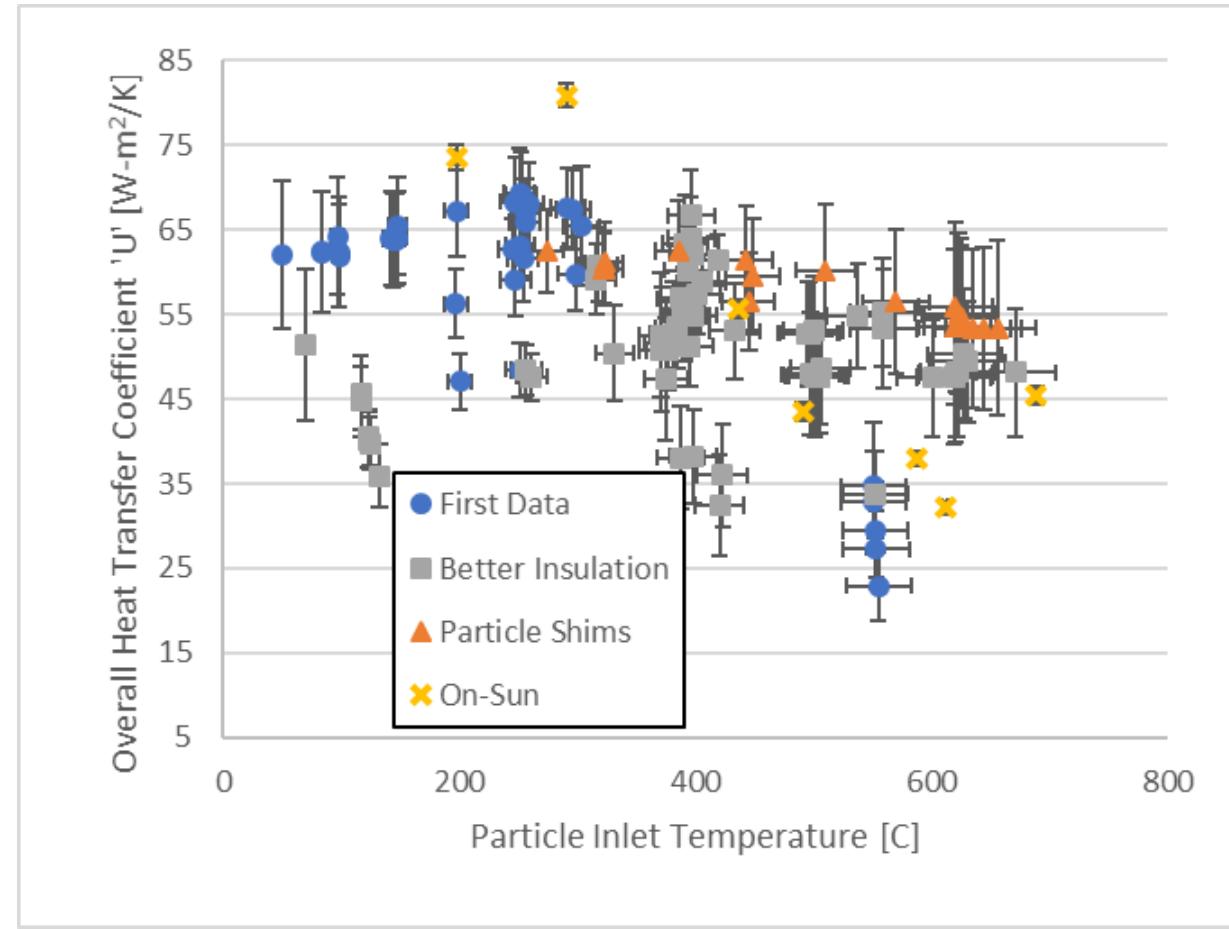
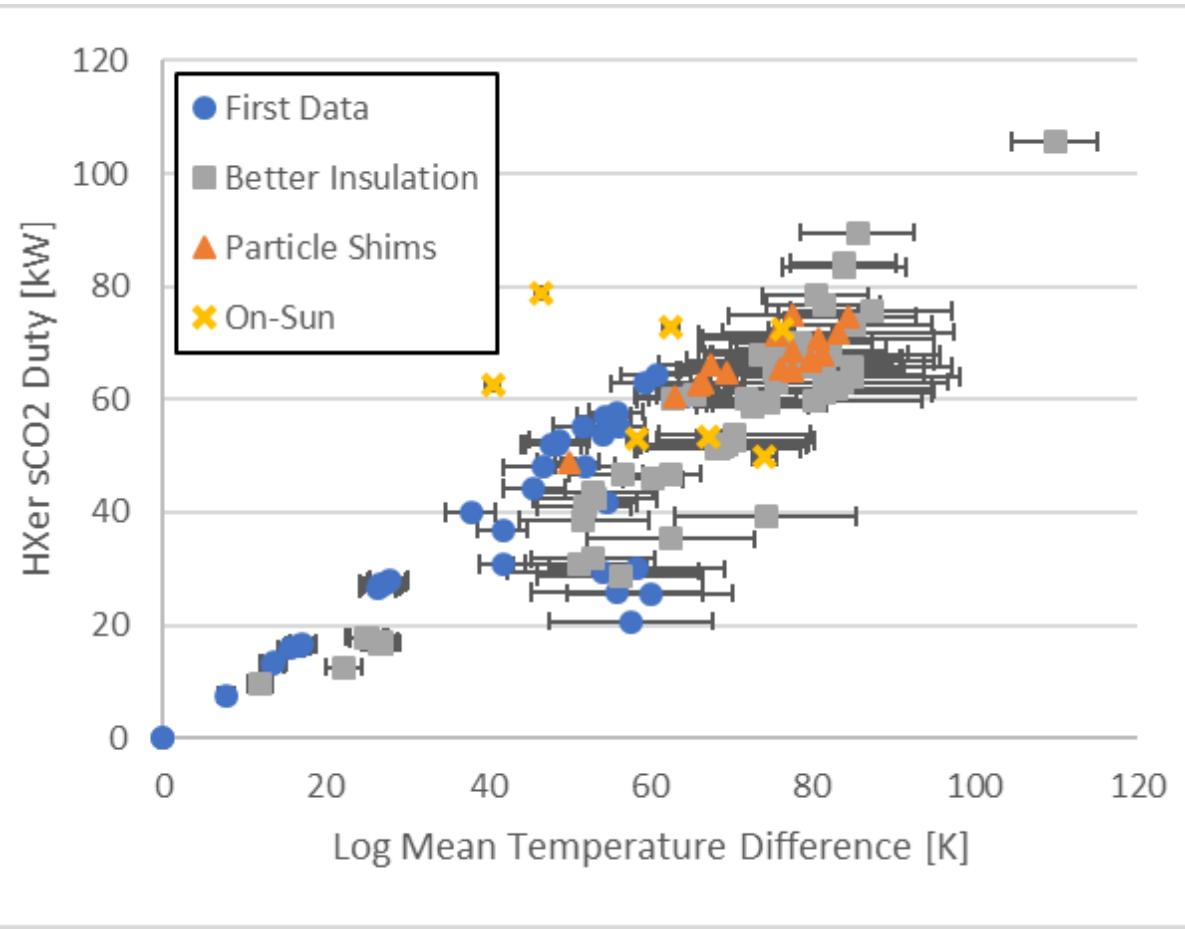
- Heat duty = 100 kW
- $T_{\text{particle,in}} = 775 \text{ }^{\circ}\text{C}$
- $T_{\text{particle,out}} = 570 \text{ }^{\circ}\text{C}$
- $T_{\text{sCO}_2,\text{in}} = 550 \text{ }^{\circ}\text{C}$
- $T_{\text{sCO}_2,\text{out}} = 700 \text{ }^{\circ}\text{C}$
- $\dot{m} = 0.5 \text{ kg/s}$



sCO₂ flow system provides pressurized sCO₂ at 550 °C to heat exchanger for test and evaluation



100 kW_t Shell-and-Plate Prototype HX Test Results



Summary



Recommendations for Next-Generation Particle/sCO₂ HX

- Manufacturing techniques that enable closer plate spacing for enhanced particle side heat transfer

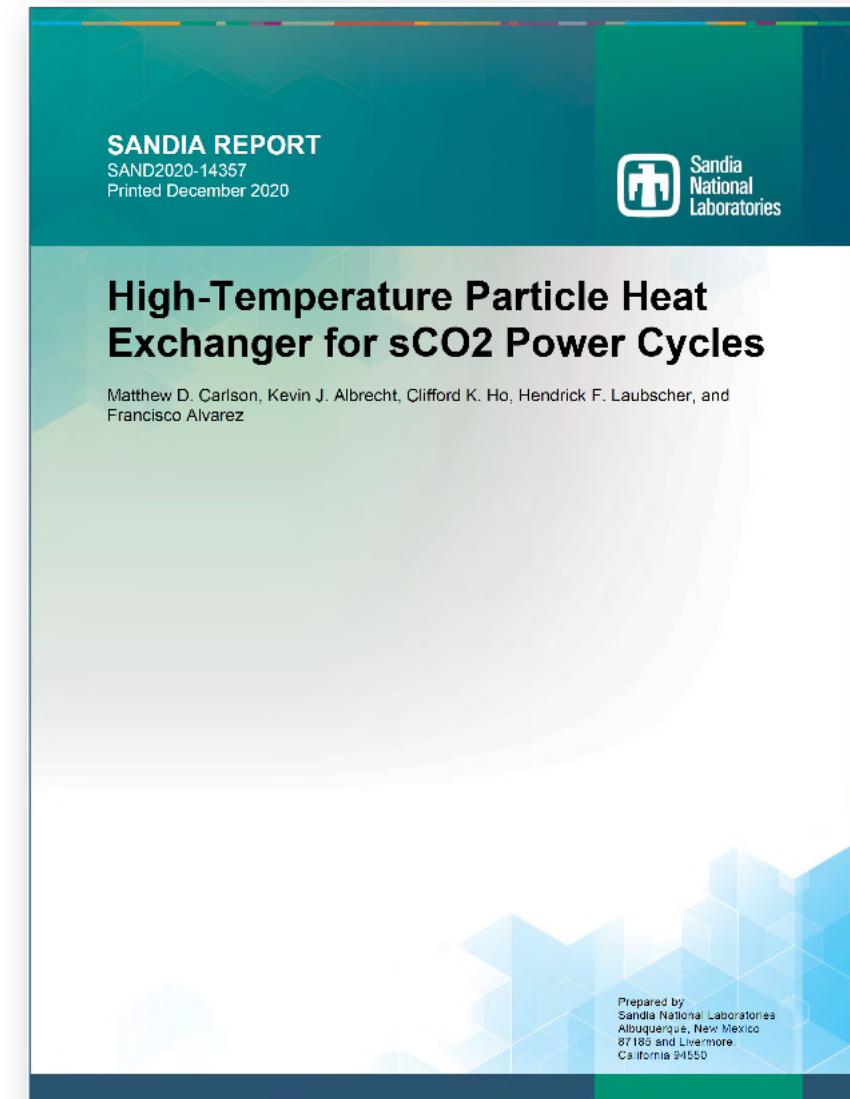
- Heat exchanger geometry for pure counter flow arrangement to reduce thermomechanical stress and improve thermal performance

- Heat exchanger geometry and manufacturing that eliminate any internal ledges causing stagnant particle regions

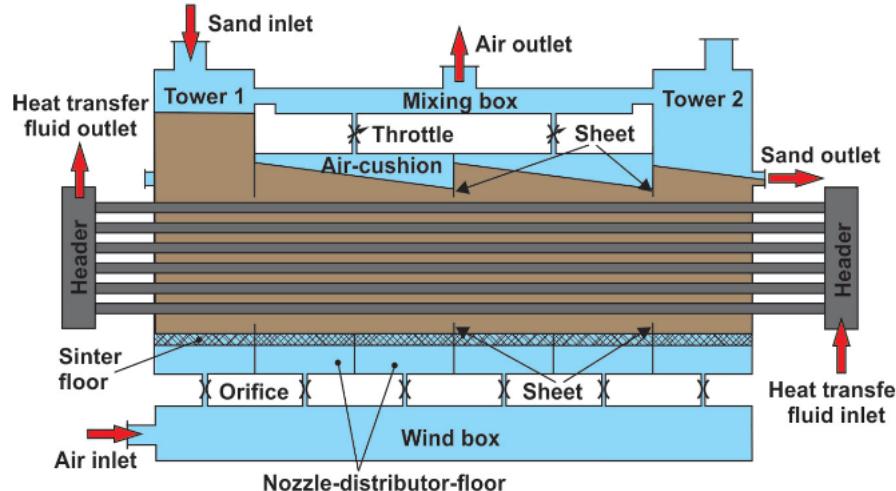
- Pipe and sCO₂ channel networks that reduce pressure drop and improve flow uniformity

- Heat exchanger particle feeder design that eliminates parallel particle flow paths causing maldistribution

- Geometries that reduce thermal mass and allow for large temperature ramp rates for reduced



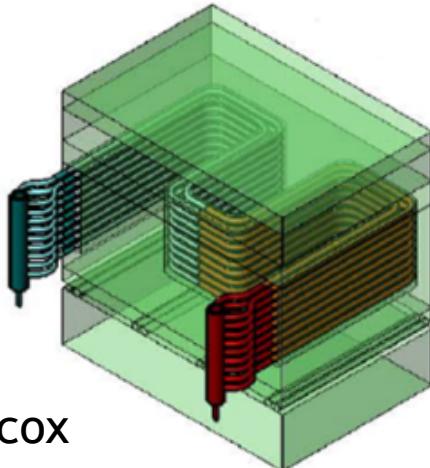
Fluidized-Bed Heat Exchangers Being Considered for Gen3



Scheme of the SandTES heat exchanger



SandTES pilot plant at TU Wien



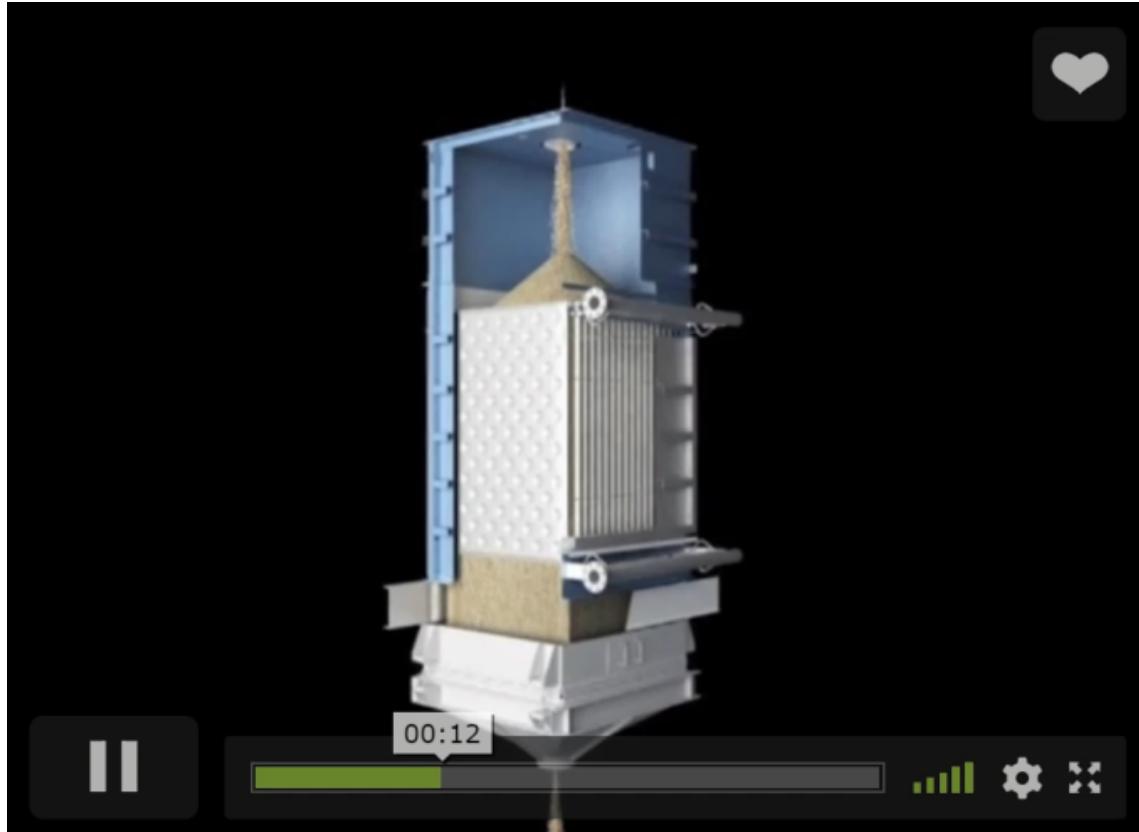
Babcock & Wilcox

	Inlet	Outlet
Pressure:	20 MPa (2900 psi)	20 MPa (2900 psi)
Temperature:	561 °C (1042° F)	732 °C (1350° F) and 800 °C (1472° F)
Material:		
Header	SA335 P91	SB167 Seamless (UNS N06617)
Header Stubs	SA213 T91	SB167 Seamless (UNS N06617)
Safe Ends	SA213 TP347H	
Section Tubes	SA213TP304H	SB167 Seamless (UNS N06617)

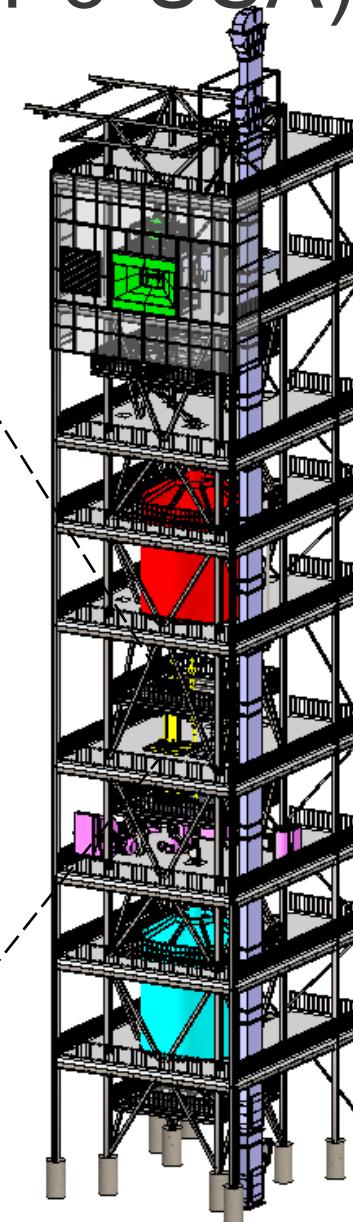
Gen3 Particle Pilot Plant (G3P3-USA)



High-Temperature Particle-to-sCO₂ Heat Exchanger
(VPE, Solex, Sandia)



<https://www.solexthermal.com/our-technology/cooling/>



Gen 3 Particle Pilot Plant

- ~1 - 2 MW_t receiver
- 6 MWh_t storage
- 1 MW_t particle-to-sCO₂ heat exchanger
- ~300 - 400 micron ceramic particles (CARBO HSP 40/70)

K. Albrecht, SNL

Acknowledgments

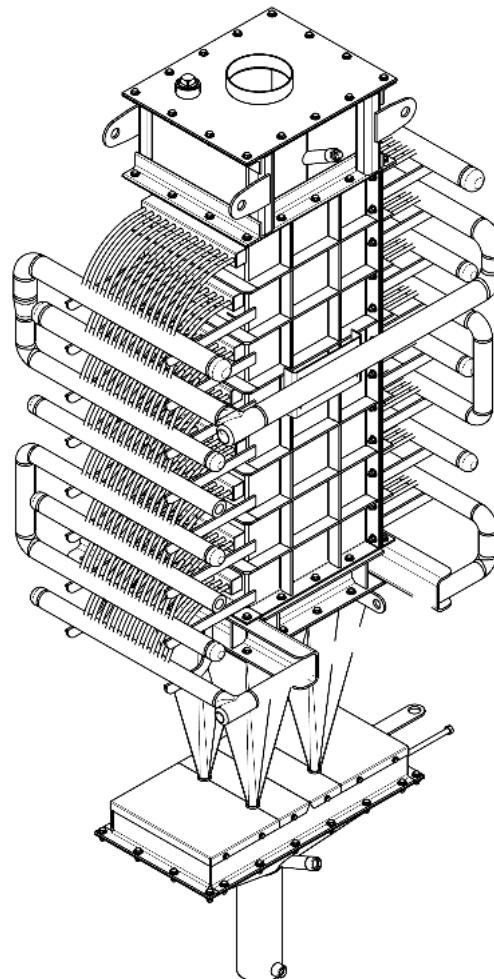
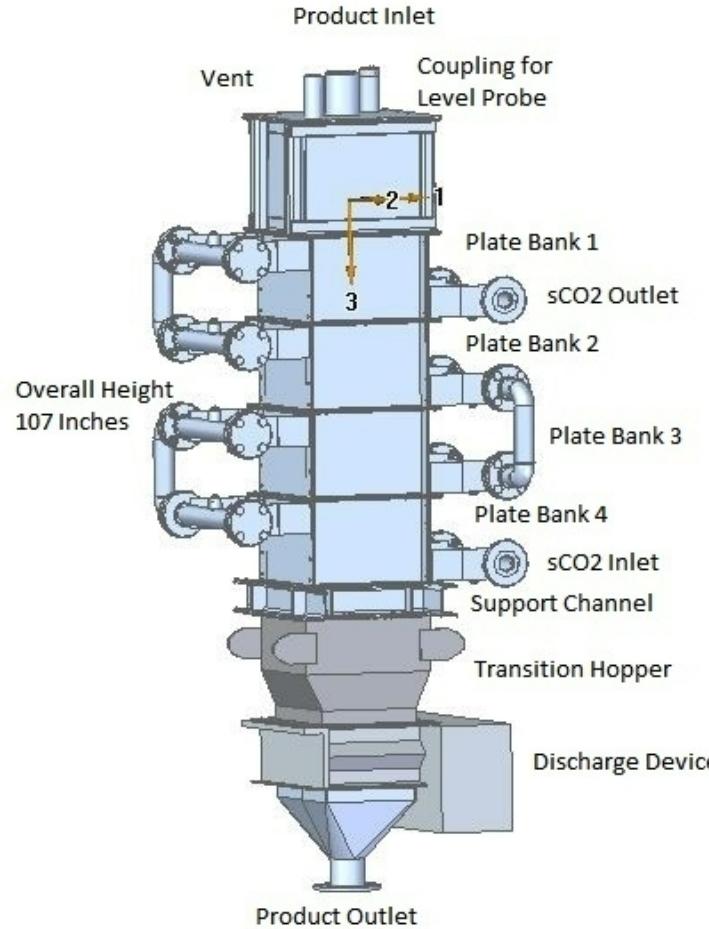


- This work is funded in part or whole by the U.S. Department of Energy Solar Energy Technologies Office under Award Number 34211
 - DOE Project Managers: Matthew Bauer, Shane Powers, Vijay Rajgopal, Levi Irwin, Andru Prescod, Mark Lausten, Avi Shultz

Backup Slides

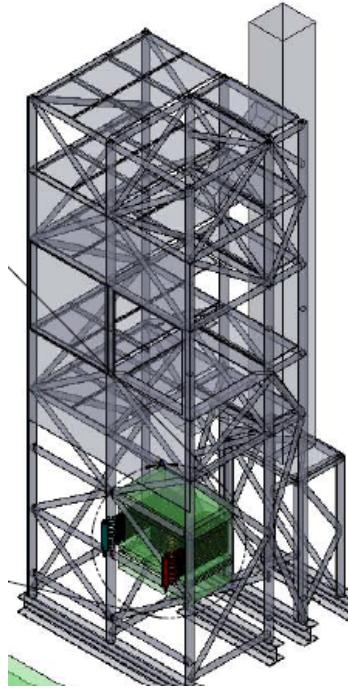
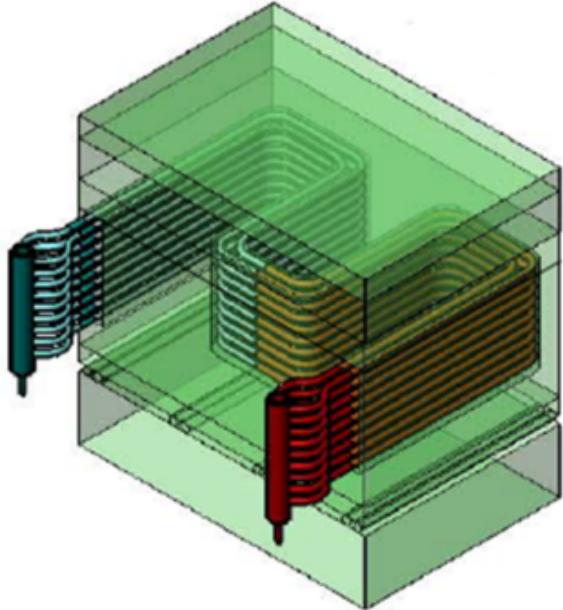


Shell-and-Plate Heat Exchanger Design (Solex, VPE, Sandia)



Product Flow Rate (kg/h)	1476
Product T in (°C)	775
Product T out (°C)	570
sCO₂ Flow Rate (kg/h)	1944
sCO₂T in (°C)	550
sCO₂T out (°C)	700
Heat Duty (kW)	100

Fluidized-Bed Heat Exchanger (B&W, NREL, Sandia)



- **Tube size:**
 - 1 inch OD tubes with 2.5 inch side spacing and 2.5 inch back spacing
- **Submerged Tube bundle:**
 - Two columns of nine tubes each
 - Tube length: 19-21 feet within the heat exchanger
 - Height: 21 inches
 - Sits approximately 8" above the air distributor
 - Six inches of fluidized solids is provided above the top of the tube bundle to cushion the top of the tubes from the incoming hot solids
 - Total depth of fluidized solids is 35 inches
 - Partition walls are tall enough to exceed the height of the expanded bed i.e., minimum 40 inches high
 - Width of the bundle channel, wall-to-wall excluding the dummy tubes, is 7.5 inches

	Inlet	Outlet
Pressure:	20 MPa (2900 psi)	20 MPa (2900 psi)
Temperature:	561 °C (1042° F)	732 °C (1350° F) and 800 °C (1472° F)
Material:		
Header	SA335 P91	SB167 Seamless (UNS N06617)
Header Stubs	SA213 T91	SB167 Seamless (UNS N06617)
Safe Ends	SA213 TP347H	
Section Tubes	SA213TP304H	SB167 Seamless (UNS N06617)

Bed-to-OD heat transfer coefficient: 477
W/m²-K

Bed-to-CO₂ overall heat transfer
coefficient (OD-based): 261(W/m²-K)