SunShot
U.S. Department of Energy

CSP Program Summit 2016

Direct s-CO_2 Receiver Development

Laboratory Proposal Development Process (LPDP) FY2012-2015

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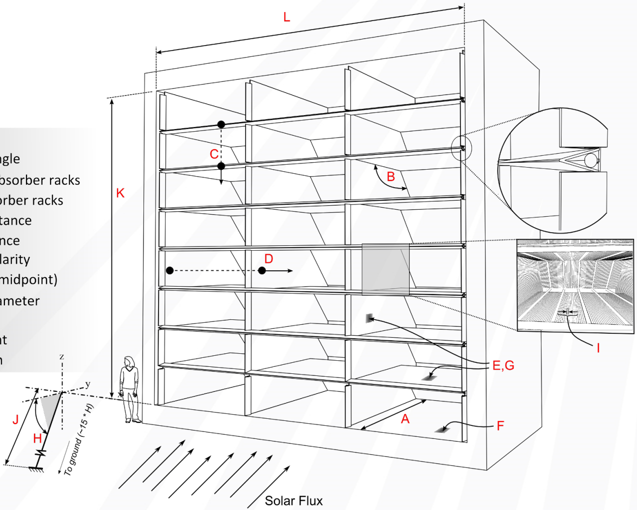
Design objectives and features

- Develop, characterize, and experimentally demonstrate a novel high-temperature direct s-CO_2 receiver
- Operate with >90% thermal efficiency at 650°C outlet temperature, 10,000 thermal cycles
- Unique use of geometry to improve performance and lifetime, reduce cost
- Use modeling techniques and tools help understand and optimize the entire technology
- Absorber is a tubular panel set arranged in a gridded geometry
- Absorber is partially absorptive to encourage flux scattering
- Heat shields protect header piping near aperture from incident flux
- Flux intensity at aperture is significantly higher than on absorbing surfaces

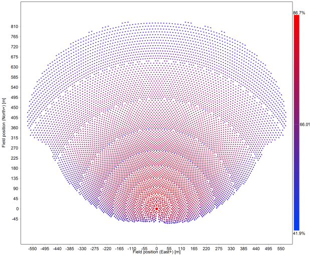
Receiver Concept

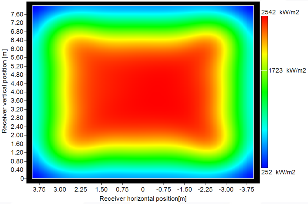
A	Total receiver depth
B	Absorber panel bend angle
C	Number of horizontal absorber racks
D	Number of vertical absorber racks
E	Absorber surface reflectance
F	Passive surface reflectance
G	Absorber surface specularity
H	Tower height (receiver midpoint)
I	Absorber tube outer diameter
J	Receiver tilt angle
K	Receiver aperture height
L	Receiver aperture width

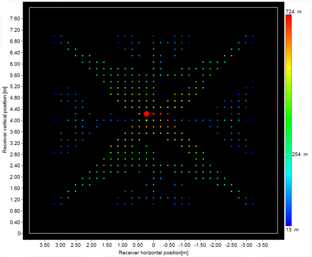


Solar Field Design

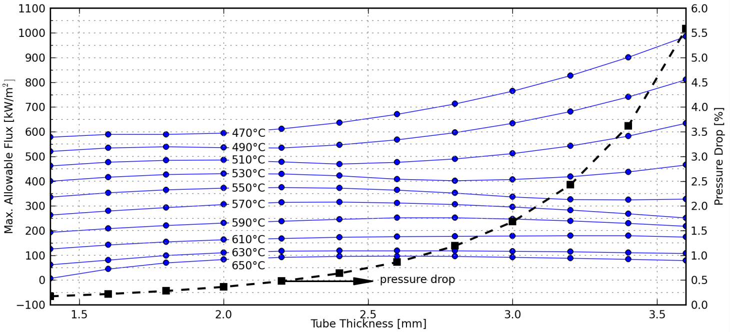
- Solar field is north-based for cavity configuration
- Flux aiming on receiver balances uniformity and spillage loss.







Maximum allowable flux drives receiver design

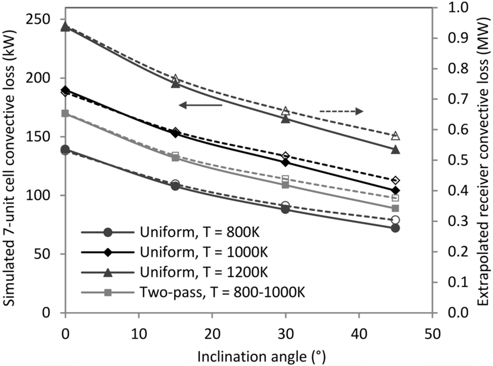


- *Creep* fatigue at inner surface is normally the limiting factor for high-pressure, high-temperature
- An optimized thickness balances max flux, pressure loss, cost

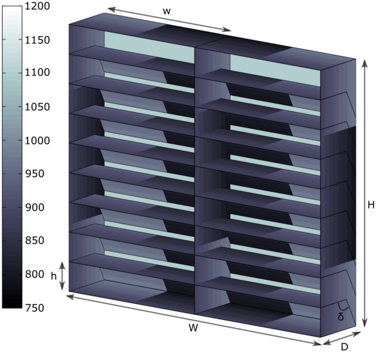
Natural convection modeling

- 3D Computational fluid dynamics (CFD) using ANSYS Fluent
  - SST k-ω turbulence model
- Full-receiver convective loss < 0.7 MW (**0.7%**) for 1000K wall temperature
  < 1.0 MW (**1.0%**) for 1200 K wall temperature

Receiver convective loss



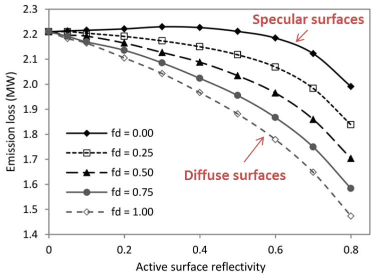
Two-pass wall T profile

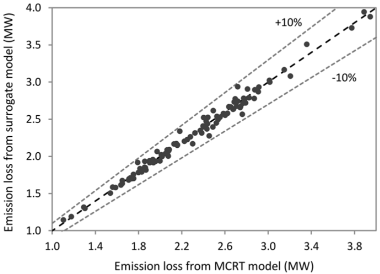


Emission loss modeling

- Design was characterized over a broad design space
- Emission loss from the base configuration is between 1.5 - 2.2 MW
- Loss can be modeled using 13-dimensional regression

$$y = \beta_0 + \sum_{i=1}^{N} \beta_i x_i + \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \beta_{ij} x_i x_j + \sum_{i=1}^{N} \beta_{ii} x_i^2$$





Efficiency Definition and Measurement

Definition

Thermal efficiency is defined as heat absorbed by the s-CO_2 fluid divided by total heat incident on the aperture of the receiver

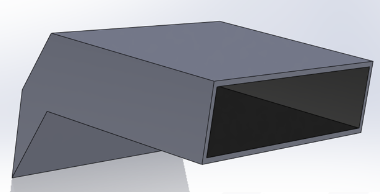
$$\eta_{therm} = \frac{\dot{m}_{CO_2}(h_{out} - h_{in})}{\int_x \int_y q''_{in}(x, y)dxdy} \tag{1}$$

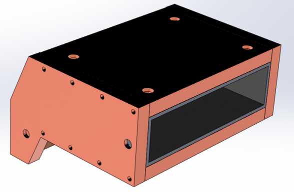
Equivalent form in terms of heat loss:

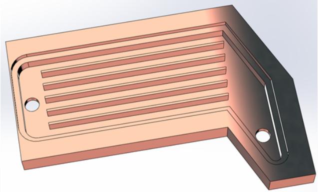
$$\eta_{therm} = 1 - \frac{1}{\iint_{x,y} q''_{in}(x, y)dxdy} \left(\overbrace{\iint_{x,y} q''_{out}(x, y)dxdy}^{\dot{q}_{refl}} + \overbrace{\sum_i \gamma(\theta)A_i(\overline{T}_i - T_\infty)}^{\dot{q}_{conv}} + \overbrace{\sum_i \sigma\epsilon A_i F_i(\overline{T}_i^4 - T_{amb}^4)}^{\dot{q}_{emit}} \right) \tag{2}$$

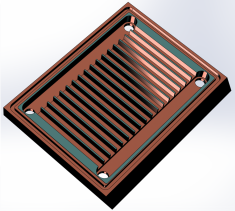
Model validation with bench-scale experiments

Calorimetric experiment measures heat absorption by unit cell

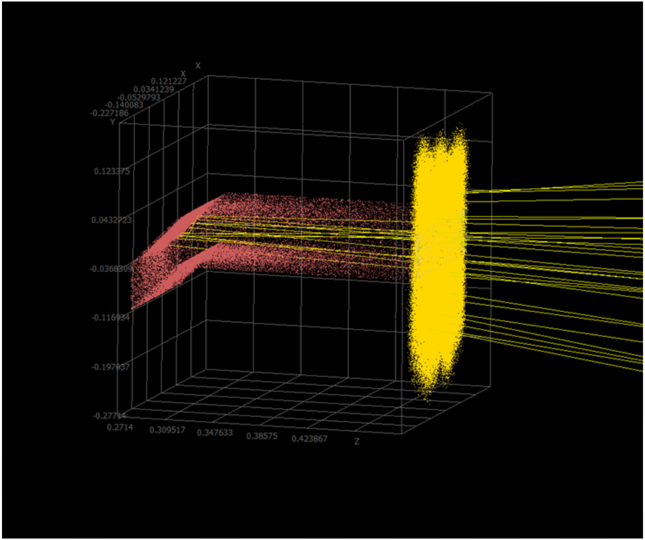






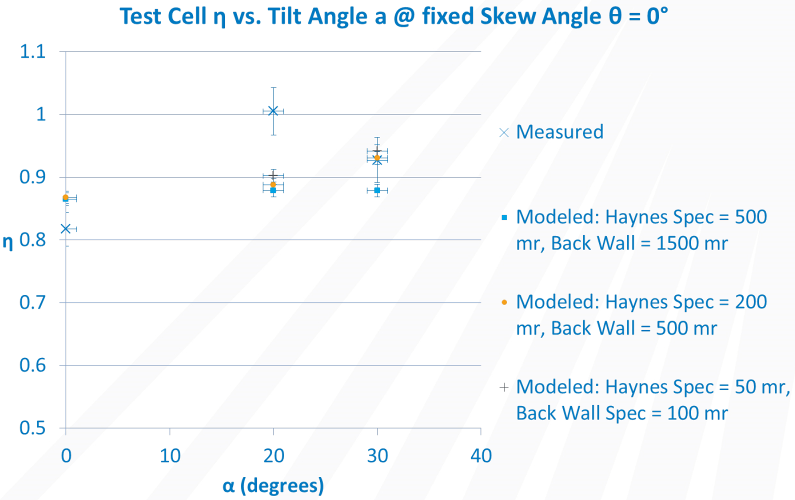


Tested at NREL's High Flux Solar Furnace



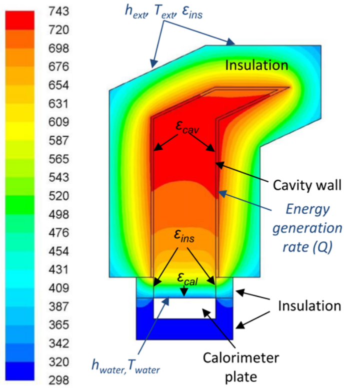
SolTrace ray trace of test cell at direct orientation ($\alpha = 0^\circ$, $\theta = 0^\circ$)

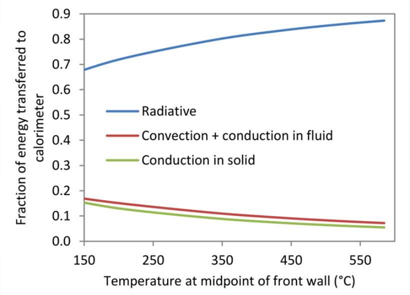
Experimental vs. model results: tilt angle subtest



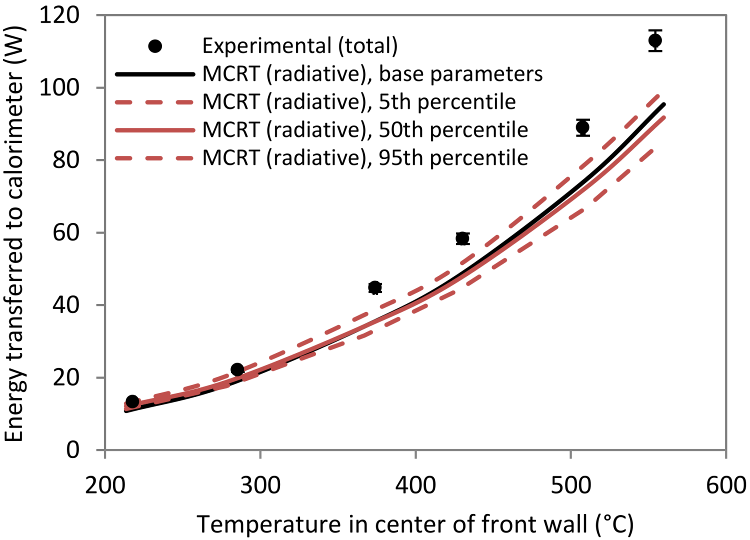
Emission loss model validation

- Analysis of full test setup using CFD / surface exchange model
- **70 - 90%** of energy transferred to calorimeter occurs by thermal radiation





Measured emissive heat transfer



Design Outcomes

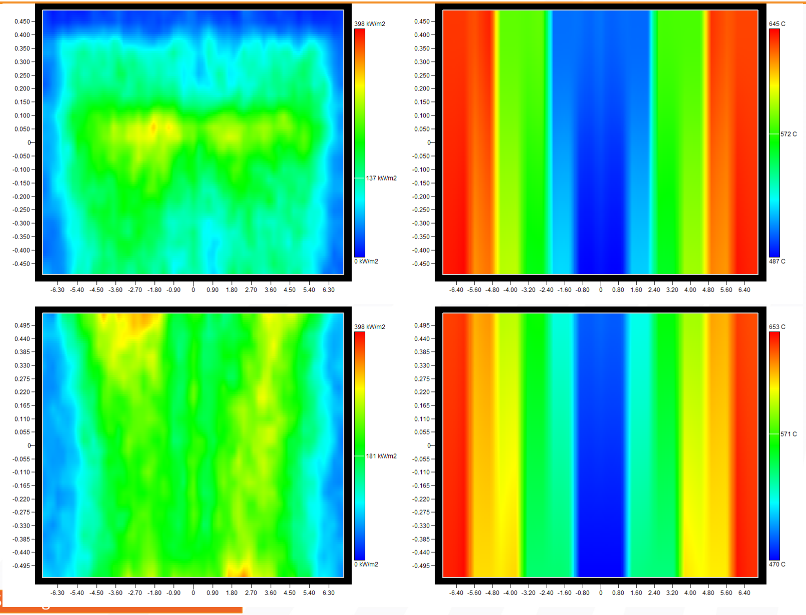
Design knowledge

- Cavity receivers have the potential to thermally out-perform external receivers
- Convective loss reduced by limiting vertical surfaces or using baffles or horizontal panels
- Receiver pressure loss significantly reduces cycle conversion efficiency of the power cycle
- Emissive and reflective loss are the most significant thermal losses this geometry
- Thermal absorption efficiency in a cavity system is only partially dependent on absorber surface reflectivity
- Tubing material usage is reduced by illuminating both sides of the panel
- Material stress drives the receiver design
  - Pressure, circumferential, radial, and gravity stresses can be significant
  - Allowable stress depends on creep, cyclical factors
  - *Data* on alloy properties are critical
- Metallurgical advances are critical for high-temperature development

Design challenges

- High-temperature optical coating
- Pressure loss through the receiver, main header piping
- Allowable surface flux as a function of HTF temperature
- Front-edge (header?) shielding for the horizontal panels
- Aperture flux distribution, solar field requirements
- Flow rate control for parallel paths
- Design optimization and high degree of dimensionality
- Cost-effective thermal storage, cycle integration
- Heat shield reflective materials
- Flux over limit due to serpentine flow path
- Shallow cavity depth to reduce gravitational moments

Design Example



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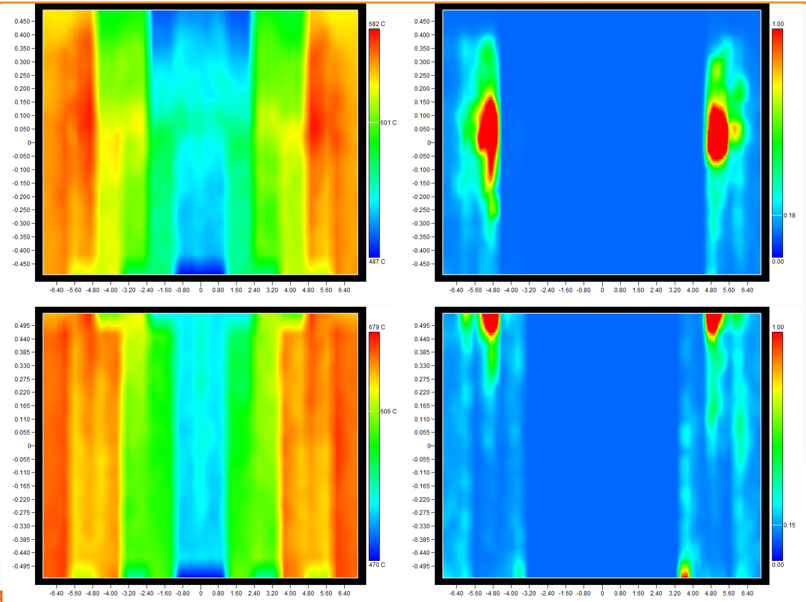

Project Achievements

I. Identified and demonstrated receiver concept that can achieve high efficiency, $> 92\%$ at design
II. Developed modeling tools and methodologies that advance receiver design
III. Experimentally validated thermal performance models
IV. Improved understanding of allowable flux, stress, and creep
V. NREL submitted provisional patent application on receiver concept