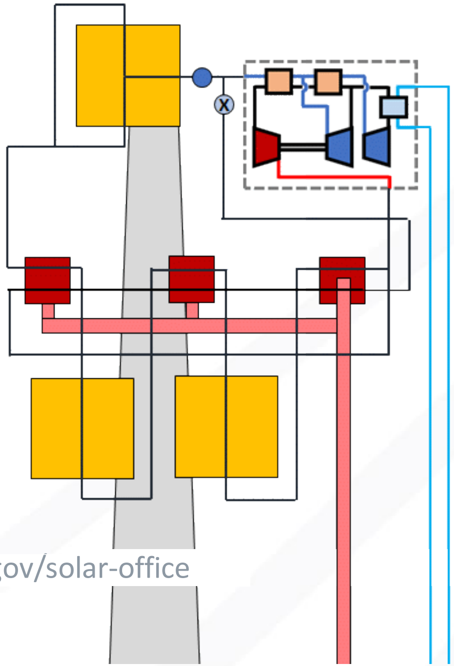
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

SOLAR ENERGY TECHNOLOGIES OFFICE

SETO CSP Program Summit 2019

Solar Receiver with Integrated Thermal Energy Storage for a Supercritical Carbon Dioxide Power Cycle

Project Overview



BraytonEnergy with SRNL and GreenWayEnergy

Award # DE-EE0007118

18-19 March 2019

Shaun Sullivan, Principal Engineer, R&D Program Manager

OVERVIEW

- Project Snapshot
- Metal Hydrides 101 …

  … and the challenge of "isothermal" energy storage (e.g. TCES, PCM)
- System Layout and Characteristics
- Novel Design Elements
- System Performance and Cost Summary
- Budget Period 3 Testing
- Project Impact

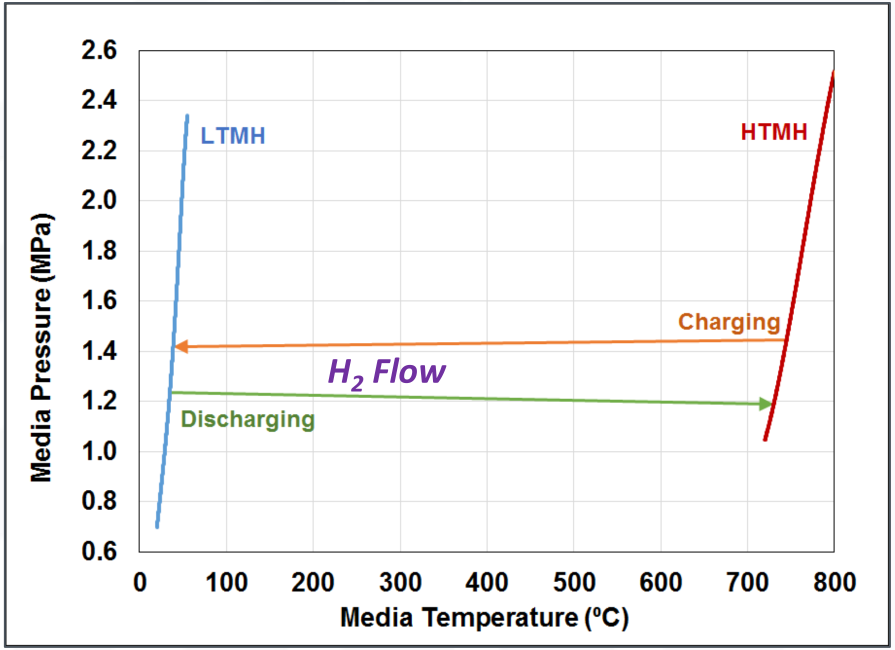
Project Snapshot

PROJECT NAME	Solar Receiver with Integrated Thermal Storage for a Supercritical Carbon Dioxide Power Cycle
FUNDING OPPORTUNITY	DE-FOA-0001186 CSP: Advanced Projects Offering Low LCOE Opportunities (APOLLO)
PRINCIPAL INVESTIGATOR	Shaun Sullivan
LEAD ORGANIZATION	Brayton Energy, LLC
PROJECT PARTNERS	Savannah River National Laboratory Greenway Energy, Inc.
PROJECT DURATION	39 months
PROJECT BUDGET	$ 3,295,953

- ✓ Develop, model, and validate via testing a set of metal hydride formulations for a CSP applications
- ✓ Specify a cost-effective CSP system integrating a metal hydrides TES solution using these media
- ✓ Design the receiver architecture and layout suitable for integration in the aforementioned system
- ✓ Design the TES metal hydride heat exchanger modules for use in the aforementioned system
- ✓ Specify and/or design the ancillary systems required to enable the aforementioned system (including tower, heliostats, valves, piping, regenerator, operating profile and control schema, etc.)
- ✓ Model the integrated system to determine its fully integrated annual/diurnal operating performance
- ✓ Evaluate the capital and operating costs, electrical production, and LCOE in commercial scenarios
- Design (✓), build, commission, and operate a test system capable of demonstrating operation and performance of the core integrated technologies developed under the scope of this program

Metal Hydrides for Thermal Energy Storage

- A well-chosen pairing of metal hydrides will enable the free flow of H_2 between the two media at the desired temperatures.
- Connecting pipes must be sized for the appropriate pressure drop to maintain intended operating temps.



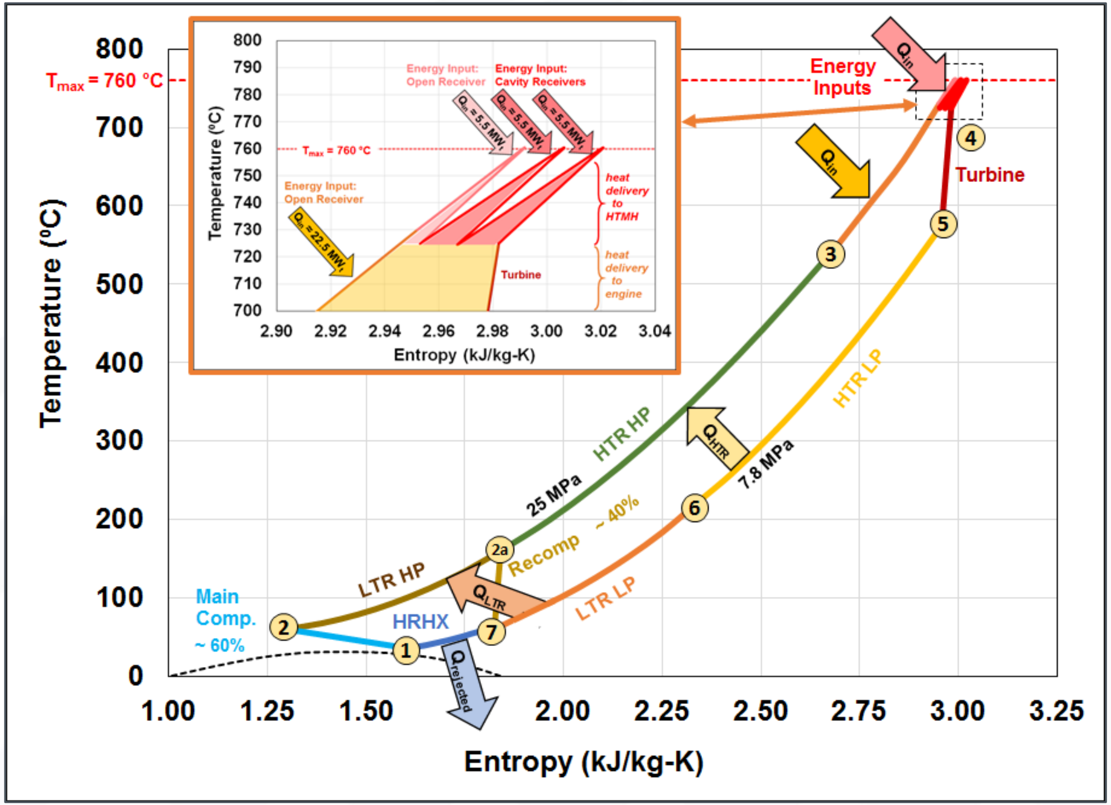
Multi-Pass TES Heat Addition

OPEN RECEIVER

- 550° to 760°C temp. rise
- Profiling allowed by heliostat aim point means average flux can be higher
- Higher re-radiation and convective losses

CAVITY RECEIVERS

- 730°C to 760°C temp. rise
- Minimal axial variation in flux because of cavity design, therefore lower average flux
- Lower re-radiation and convective losses



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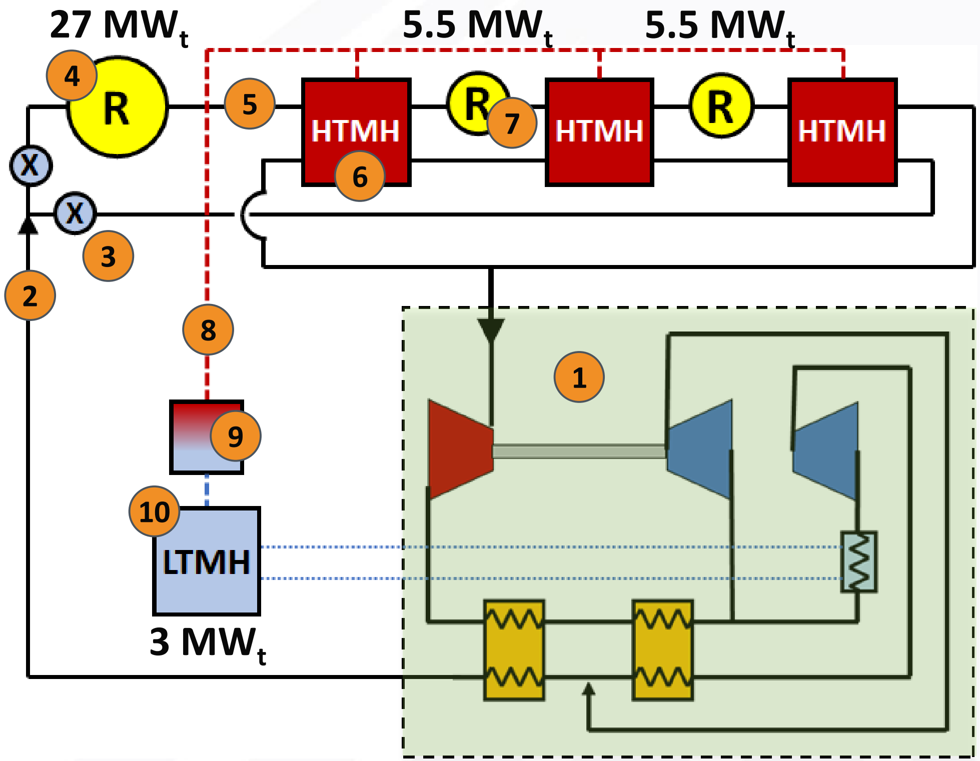
Integrated System Layout

1. RCBC sCO_2 power block
   - *nominally the STEP engine*
2. Low temp. (~ 570 °C) piping
3. Low temp. (~ 570 °C) valves (x2)
4. 27 MW_t open receiver
5. High Temp (~ 760 °C) piping
6. 5.5 MW_t HTMH TES HEX (x3)
7. 5.5 MWt cavity receiver (x2)
8. Hydrogen (~720 °C) transport pipe
9. Regenerator
10. ~ 3 MW_t LTMH TES HEX



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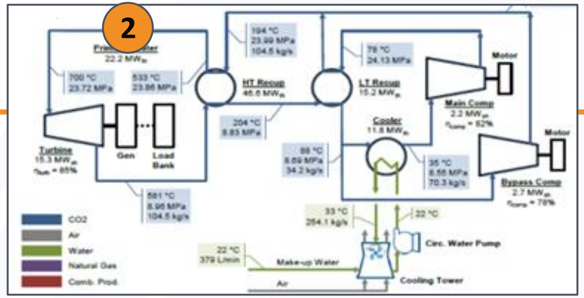
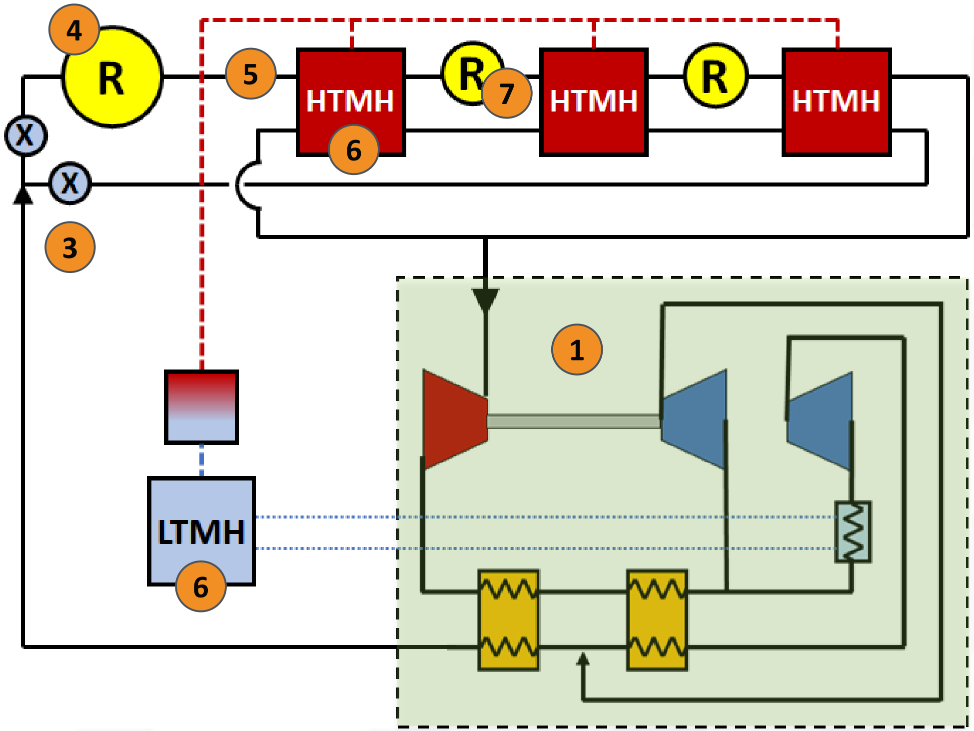
Key Characteristics

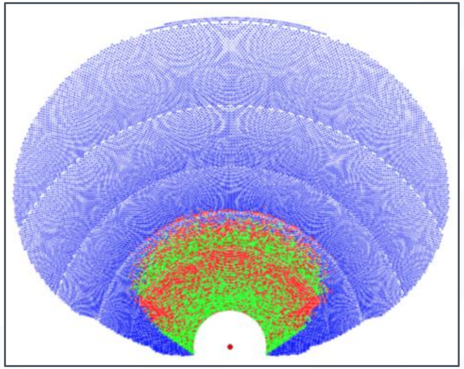




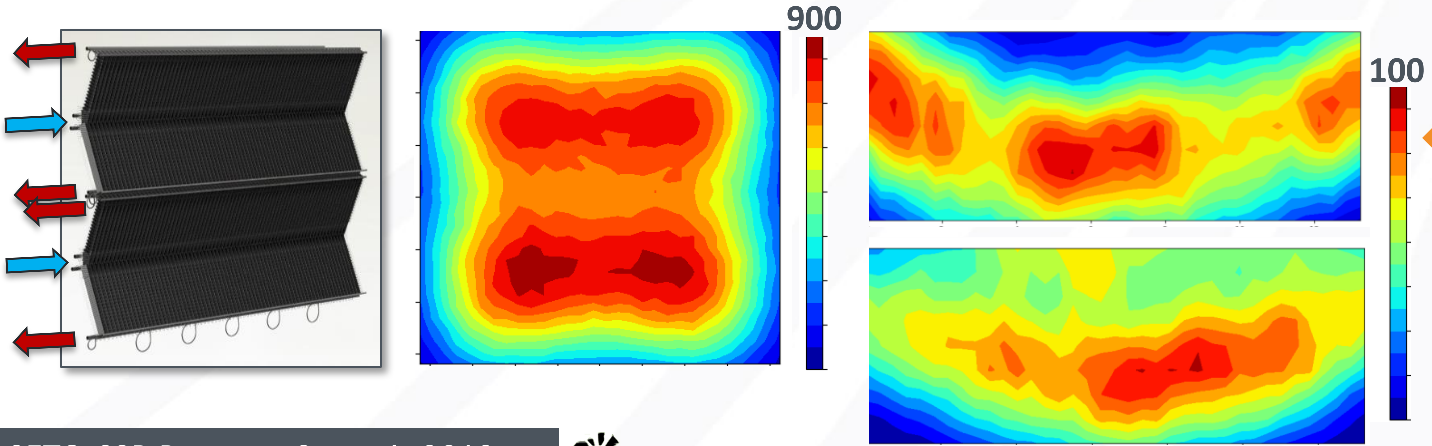
1. Power block provides the working fluid circulation through the receiver and TES
2. Various operating conditions manifest as minor DP changes across the RCBC PHX
3. Cold flow valves allow full control over all operating conditions
4. Open receiver leverages Gen3 sCO_2-receiver development
5. System layout minimizes costly hot piping
6. HTMH and LTMH HEX designs leverage Gen3 PCM development
7. Cavity receivers enable low-flux near-isothermal heat addition and reduced thermal losses

Heliostat-Based Control Features

Program leverages Gen3 advancements in heliostat control to expand system capabilities



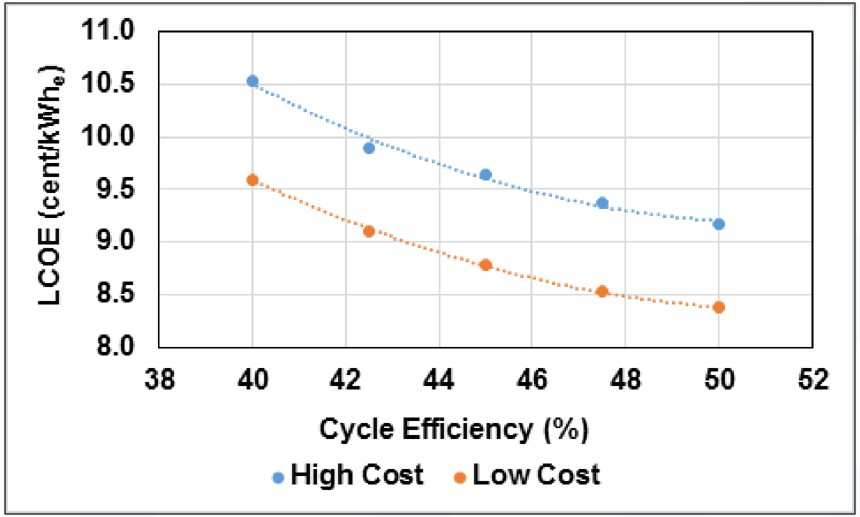
- Multi-receiver targeting
  - Closest heliostats are allocated to cavity receivers
    - *Reduced spillage*
    - *Small apertures*



- Flux Profiling
  - Aligns peak fluxes in open receiver with coldest fluid

System Performance, Cost, and MH Customization

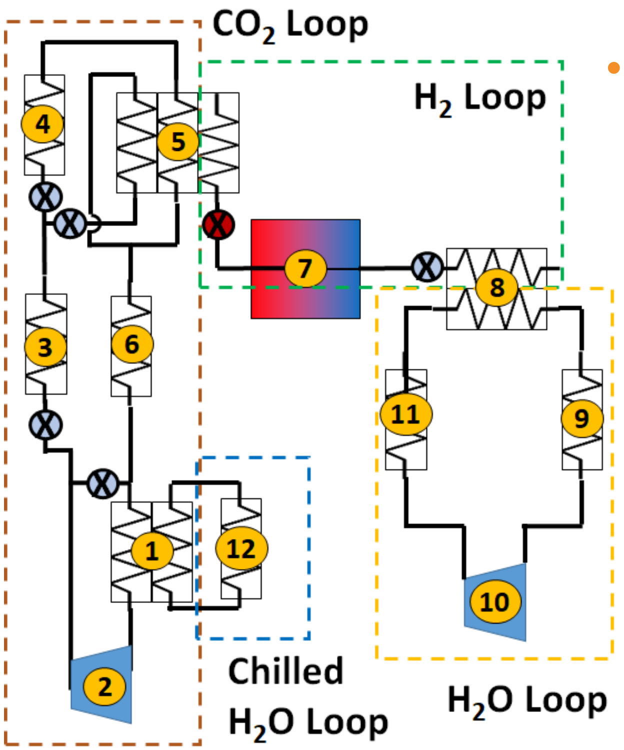
- Metal hydride customization produced significant system LCOE benefits
- System meets LCOE targets for a flexible-dispatch peaker-type system



PARAMETER	UNITS	CHARGE	DISCHARGE
Receiver Power	MW_t	34	0
Storage Power	MW_t	12	-23
Engine Power	MW_e	9.5	11.0
Hours of Operation	hr	8	4
Efficiency	%	43.2%	47.0%
Weighted Efficiency	%	44.5%	

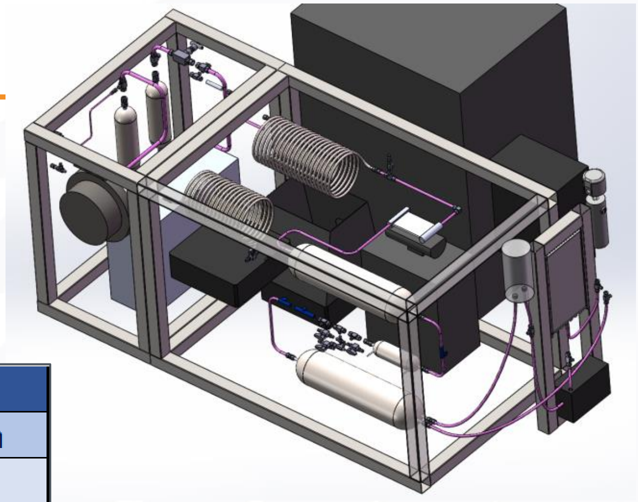
PARAMETER	UNITS	BP1	BP2	Δ
H_2 Weight Capacity	%	2.40%	1.70%	-29%
Therm. Cond. k	W/m-K	3.5	5.8	66%
Bulk Density	kg/m^3	1400	2100	50%
Specific Heat	kJ/kg-K	0.8	1.1	38%
Reaction Enthalpy	kJ/mol_{H2}	110	96	-13%
Reaction Entropy	kJ/mol_{H2}	0.130	0.130	0%
EST. ΔLCOE	%			25.8%
	$\$/kWh_e$			0.026

BP3 Demonstration System



- Designed for 2 kW power, 1 hr storage

NUMBER	COMPONENT
1	CO_2 heat rejection
2	CO_2 pump
3	CO_2 pre-heater
4	CO_2 receiver
5	HTMH HX
6	Air Pre-cooler
7	H_2 regenerator
8	LTMH HX
9	Water heat rejection
10	Water pump
11	Water heater
12	Water chiller



- Uses CO_2 as the working fluid at full temperature and pressure
- Significant effort has been made to design a system that will match the full scale system as closely as possible

Project Impact

- BP3 experimental testing validates the operation + performance of key integrated components
- Delivery of a final CSP system design that:
  - Leverages close-coupling and highly-integrated holistic system design to achieve aggressive performance targets
  - Incorporates a TCES system with 4 hours of storage
  - Provides flexible operation and dispatchable power
  - Leverages factory-assembled and truck-transportable components to minimize installation costs and meet LCOE targets
  - Due to the ambient temperature storage of the LTMH, the system may be modified for longer-duration long-term storage applications
    - e.g. ARPA-E days (days or weeks worth of storage, with days or weeks or even months of storage time)

Demonstration of cost-effective CSP with integrated isothermal* energy storage for peaker-type applications

*(e.g. PCM, TC)

CSP **APOLLO**

Round-the-Clock Solar Energy

with **Increased Storage, Flexibility,**

and **Dispatchability**

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THANK YOU

We gratefully acknowledge the support and funding of the United States Department of Energy Office (via DE-EE0007118) without which this work would not have happened

Circulator Performance Modeling Assumptions

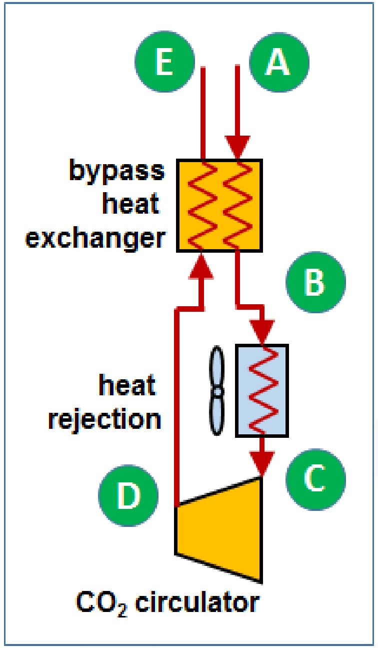
PARAMETER	UNITS	VALUES
ALL SYSTEMS		
Circulator Efficiency	%	80
Heat Loss per Pipe Run	°C	5
DP/P per Pipe Run	%	2.0%
Receiver Pressure Drop DP/P	%	4.0%
Receiver Efficiency	%	90.0%
ALL COLD CIRCULATORS		
Heat Rej. Approach Temp	°C	20.0
Heat Rej. Heat Exchanger	%	2.0%
BASELINE COLD CIRCULATOR		
Bypass. Approach Temp	°C	20.0
Bypass HEX DP/P (each side)	%	2.0%
RECOMPRESSION CIRCULATOR		
HTR Effectiveness	%	94.4%
HTR DP/P (each side)	%	1.0%
LTR Effectiveness	%	94.4%
LTR DP/P (each side)	%	1.0%
INTERCOOLED CIRCULATOR		
Intercooler Approach Temp	°C	20
Intercooler DP/P	%	2.0%

- Circulator configurations are assumed to be 1-pass; therefore mass flow is determined from required sensible heat gain over calculated temperature rise

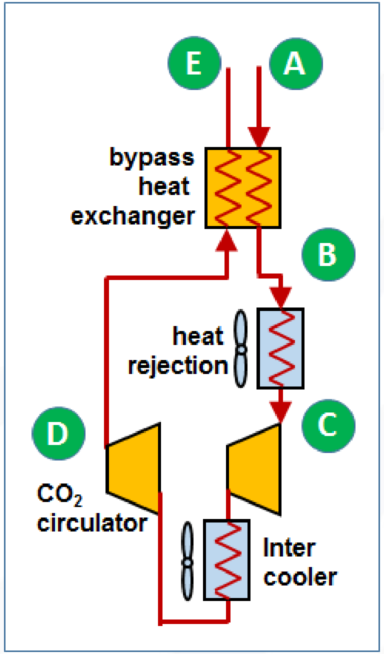
- Other configurations also evaluated, including:
  - Air circulators
  - Topping air-Brayton cycles
  - Topping sCO_2 RCBC cycles

Circulator Layout Study

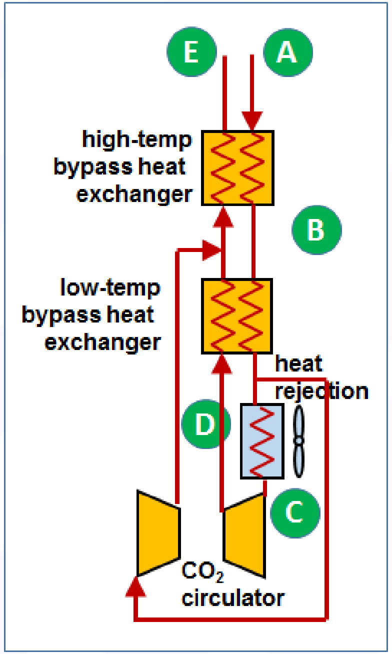
COLD CIRCULATOR



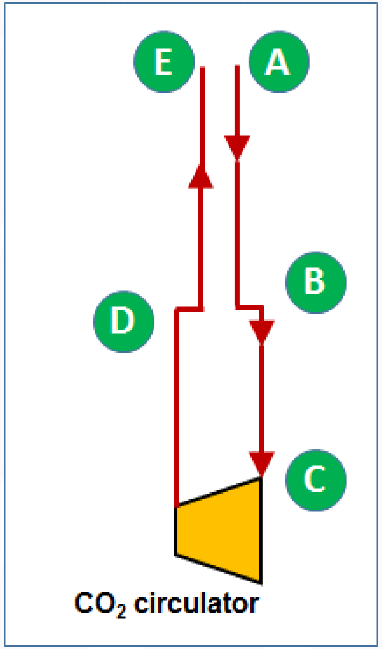
INTERCOOLED CIRC.



RCBC CIRCULATOR



WARM CIRCULATOR



Circulator Performance Study

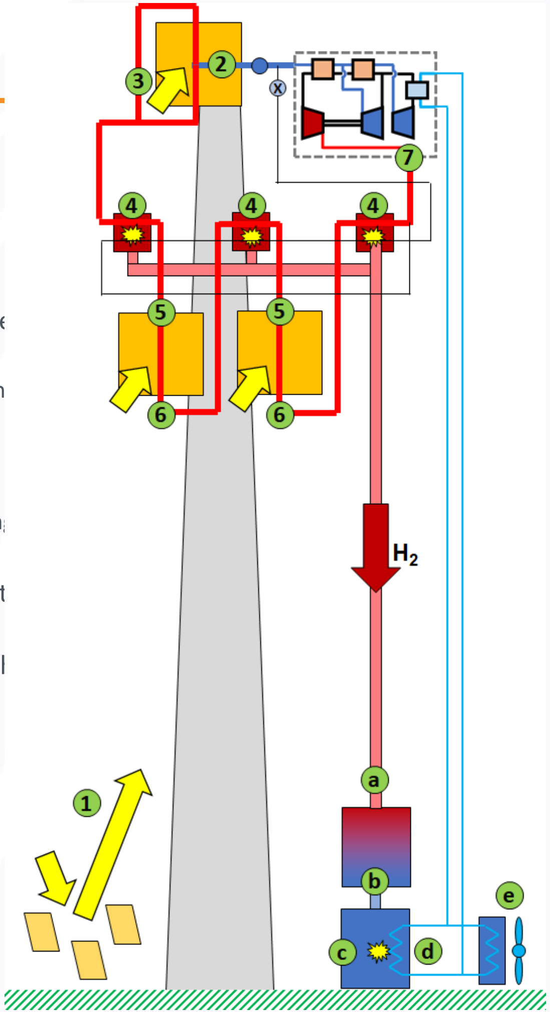
- Intermediate loop introduces:
  1. Large operating power parasitic
  2. Large heat rejection loss, or
  3. Large heat exchangers

4. Instead, use a circulator that is already paid for…

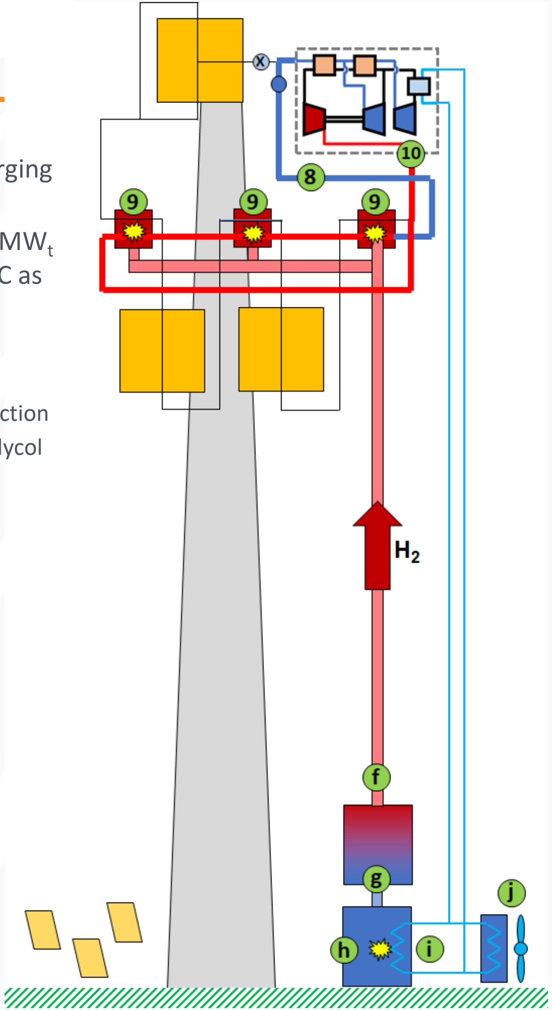
		SIMPLE DESIGN POINT CO2 CIRCULATOR STUDY				
PARAMETER	UNITS	Baseline	Intercooled	Re-compression	Hot	Integrated 10 MW_e sCO_2 RCBC
Design Pt. Circ. Power	MW_e	-1.6	-1.7	-1.8	-4.3	-1.7
Equiv. Net Circ. Power	MW_e	*-1.0*	*-1.0*	*-1.0*	*-2.4*	*-0.9*
Design Pt. Receiver Input	MW_t	49.2	50.1	46.9	37.6	37.3
$\Delta_{receiver\ capacity}$	%	*31.9%*	*34.3%*	*25.8%*	*0.9%*	-
Equiv Receiver Input	MW_t	*31.1*	*31.6*	*29.7*	*24.3*	*21.7*
Bypass HEX Duty	MW_t	80.6	82.3	66.7	-	-
Rejection HEX Duty	MW_t	8.9	7.2	6.8	-	-
Intercooler HEX Duty	MW_t	-	2.7	-	-	-
Equiv. Thermal Loss	MW_t	*13.5*	*24.8*	*16.1*	*0.0*	*0.0*
LTR HEX Duty	MW_t	-	-	11.4	-	-
TES HEX Duty	MW_t	22.4	22.4	22.4	22.4	22.4
TOTAL HEX Duty	MW_t	111.9	114.6	107.3	22.4	22.4
Required Field Input	MW_t	**73.3**	**75.2**	**69.0**	**52.8**	**52.5**
Net Equiv. Sys. Efficiency	%	**22.6%**	**15.9%**	**19.6%**	**31.2%**	**42.1%**

Values shown are for design point, normalized to a 10 MW_e STEP-like sCO_2 RCBC system with 4 hours of storage

1. Concentrated sunlight from the solar field intersects the open receiver absorber surface
2. Inlet sCO_2 at HTR HP outlet conditions, 105 kg/s, 550 °C, 25 MPa enters the open receiver
3. ~28 MW_t heat addition to the open receiver produces sCO_2 outlet temperature of 760 °C
4. High temp. sCO_2 is conveyed into a heat exchanger containing HTMH at 720 °C. The sCO_2 transfers MW_t into the HTMH, which undergoes an ENDOTHERMIC reaction at 720 °C; the absorbed heat bre bonds and releases gaseous hydrogen
   a. As local partial pressure of H_2 increases, it permeates through the HTMH and flows down transport pipe in regenerator
   b. High temp. H_2 gas transfers sensible heat into the regenerator and leaves at ~60 °C
   c. H_2 enters and bonds to the LTMH media, releasing heat in an EXOTHERMIC reaction
   d. To prevent LTMH temp. rise – which would stop the reaction –released heat is removed via a glycol coolin
   e. Heat addition to glycol is rejected to ambient via the power block pre-cooler
5. After delivering heat to the HTMH bed, sCO_2 exits the HTMH heat exchanger at ~735 °C; it then ent the first cavity receiver at this condition
6. The sCO_2 is heated back up to 760 °C after absorbing ~5.5 MW_t. Due to the high fluid inlet temp., tl peak flux on the cavity receiver surface is low enough to maintain metal temperatures below their critical limits. This results in a large receiver surface area, which justifies the cavity receiver configuration (with center-aimed aperture) to minimize thermal losses to ambient.
7. HTMH exit flow then enters the power block turbine to:
   - Power the compressors,
   - Generate electricity, and
   - Provide sCO_2 fluid circulation for the integrated system



8. Inlet sCO_2 at HTR HP outlet conditions, 105 kg/s, 550 °C, 25 MPa enters HTMH counterflow to charging direction
9. sCO_2 is conveyed into a heat exchanger containing HTMH at 720 °C. The “cool” sCO_2 absorbs 22.5 MW_t from the HTMH, which then absorbs gaseous H_2 and undergoes an EXOTHERMIC reaction at 720 °C as chemical bonds are formed
   - f. As its partial pressure decreases, more H_2 is pulled from the LTMH through the regenerator
   - g. Low temp. 60 °C H_2 gas from the LTMH absorbs heat in the regenerator and leaves at ~720 °C
   - h. The reduced partial pressure pulls more H_2 out of the LTMH, breaking the bonds in an ENDOTHERMIC reaction
   - i. To prevent LTMH temperature decrease – which would stop the reaction – heat is added at ~60 °C via a glycol cooling loop
   - j. Heat is added to the glycol loop by absorbing some of the cycle heat rejection
10. HTMH exit flow then enters the power block turbine to:
    - Power the compressors,
    - Generate electricity, and
    - Provide sCO_2 fluid circulation for the integrated system



1.2.1 – Solar Modeling Details

- <u>Heliostats:</u>
  - H = 4m, W = 8m
  - Individually-focused
- Small heliostats require significantly more computation time
- No noticeable difference in the results was observed by using larger heliostats (with individual-focusing)
  - 1.2% lower capital cost due to slightly reduced spillage
  - Tested keeping other system parameters constant
- <u>Tower Costs:</u>
  - WithOUT piping:

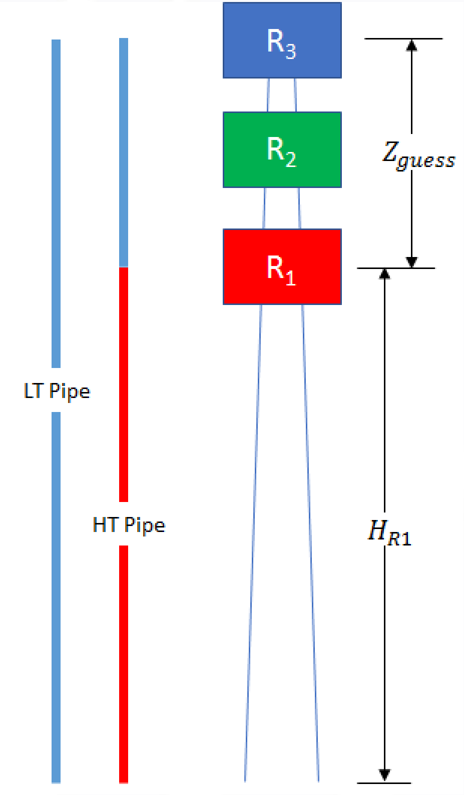
$$c_{tower} = c_{fixed} e^{A(H_{R1}+Z_{guess})}$$

  - With piping: (no connection distances included)

$$c_{tower} = c_{fixed} e^{A(H_{R1}+Z_{guess})} + c_{HT} H_{R1} + c_{LT}(H_{R1} + 2Z_{guess})$$

<u>SolarPILOT form:</u>

$$c_{tower} = c_{fixed} e^{H_{R1}}$$



1.2.2 – Field Modeling: Multiple Aimpoint

M. Wagner
NREL
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Premise

- In order to accommodate the multi-pass receiver concept, significant modifications are required to the solar field design and aiming strategy
  - Most cost-effective arrangement involves multiple receivers on a tower at varying elevations

Challenge

- Conventional heliostat field design distributes heliostat aimpoints over a **single** surface to minimize spillage and observe maximum flux limits
- For multiple receivers and a single heliostat field, each heliostat can be assigned to one of the several receivers
- Introduces substantial additional complexity in the aiming strategy

Problem classification

- Two problem classes must be addressed
  1. Selection of the optimal set of heliostats for final layout
  2. Specification of heliostat aimpoints w/r/t sun position

Outcome summary

- Q1 work developed and exercised new methodologies for handling multiple receivers within NREL's SolarPILOT™ software
- Methods utilize a linear programming technique
  - identifies the optimal set of heliostats
  - solves a sister problem to determine heliostat aimpoints that maximize power while ensuring balance among all receivers

1.2.2 – Field Modeling: Multiple Aimpoint

M. Wagner
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Design problem

- Set of all heliostats H, receivers R
- Power from h to r denoted as variable set $x_{h,r}\ \forall h \in H,\ r \in R$
- Parameter C_h is cost of energy produced by heliostat h
- Power from each h at design is $Q_{h,r}\ \forall h \in H, r \in R$
- Power required by r at design is Q_r^R
- Objective: $\boldsymbol{minimize} \sum_{r \in R} \sum_{h \in H} C^h x_{h,r}$

Constraints:

$\sum_{h \in H} Q_{h,r} x_{h,r} \geq Q_r^R\ \forall r \in R$	The design power requirement for each receiver
$\sum_{r \in R} x_{h,r} \leq 1\ \forall h \in H$	Total power from each h to all r cannot exceed unity
$0 \leq x_{h,r} \leq 1$	Physical limits on power from h

Aimpoint problem

- Subset of heliostats in final layout: $\mathcal{H}$
- power delivered from heliostat h to receiver r at operating condition $Q_{h,r}\ \forall h \in \mathcal{H}, \forall r \in R$
- Objective: $\boldsymbol{maximize} \sum_{r \in R} \sum_{h \in \mathcal{H}} Q_{h,r} x_{h,r}$

Constraints:

Proportional power of each receiver is consistent with the design proportionality

$$\sum_{h \in \mathcal{H}} \left(\frac{Q_{h,0} x_{h,0}}{\Gamma_0^R} - \frac{Q_{h,r} x_{h,r}}{\Gamma_r^R} \right) = 0\ \forall r \in R$$

1.2.2 – Field Modeling: Multiple Aimpoint

M. Wagner
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

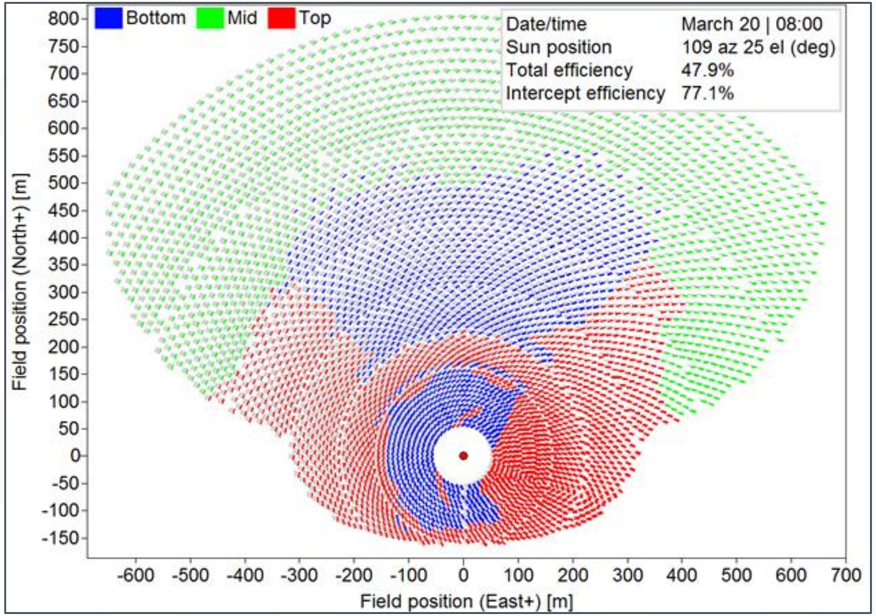
Case:

- Optimized system, uniform power among 3 receivers
- Aimpoint map shown for equinox, summer & winter solstices

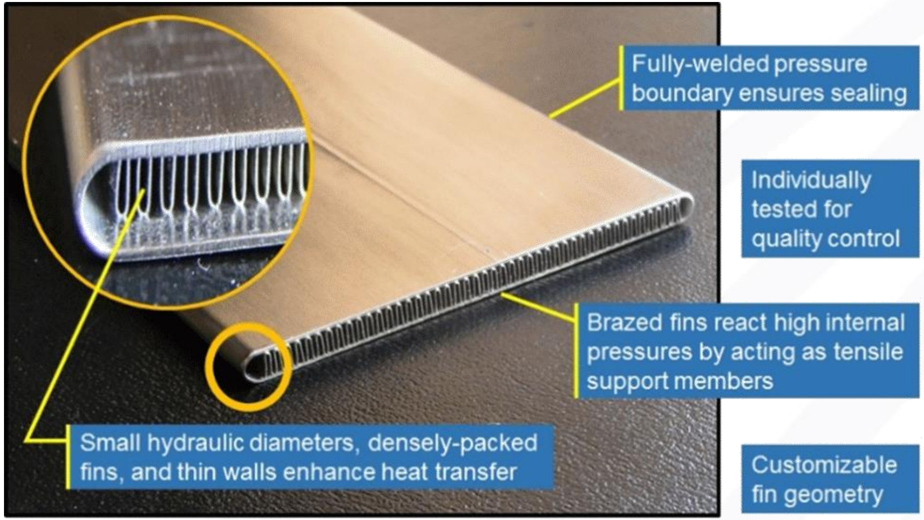
Results:

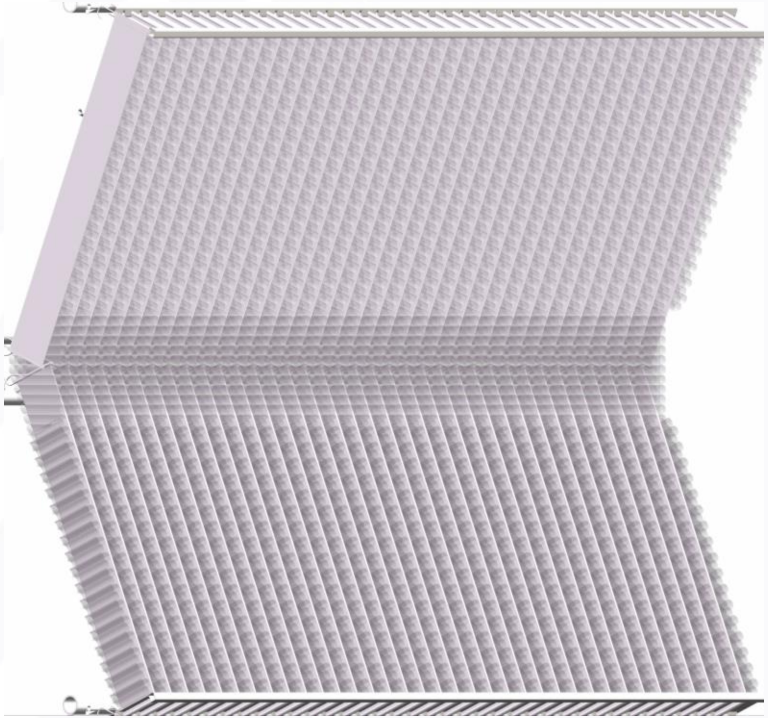
- Prediction of the relationship between heliostat position and receiver assignment is difficult
- Factors influencing the final aimpoint strategy include
  - blocking and shadowing
  - view factor between the heliostat and receiver
  - position of the reflected image on the receiver aperture

- **The methodology identifies the optimal layout and aiming strategy for multiple receivers using a linear model with little loss of fidelity**



Phase 3 Risk Retirement





1.2.2 – Field Modeling: Flux Profiling

M. Wagner
NREL NATIONAL RENEWABLE ENERGY LABORATORY

Premise:

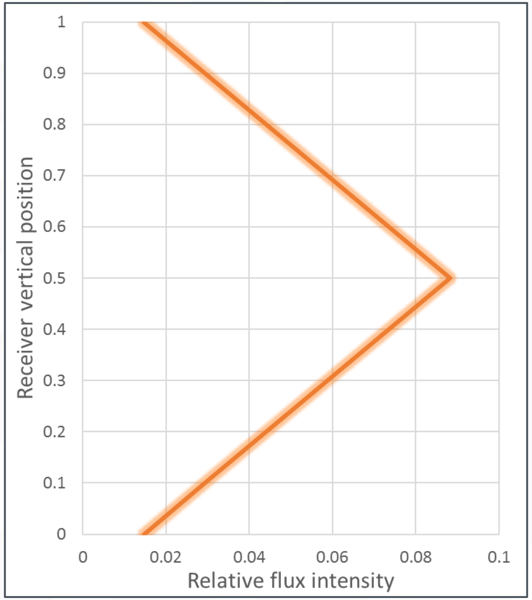
- Advanced receivers at high temperature require unique incident flux patterns to maintain allowable surface temperature

Goal:

- Develop a method for enforcing local receiver flux limits and modifying the aimpoint strategy to accommodate arbitrary flux profiles in SolarPILOT

Current capability:

- Enforce uniform flux using iterative approach, assign aimpoints using random distributions, or use simple aim points and process using dedicated programs



Desired flux profile for the gas receiver. The highest intensity flux is near the vertical midpoint with reduced intensity near the edges

Receiver Flux Profiling

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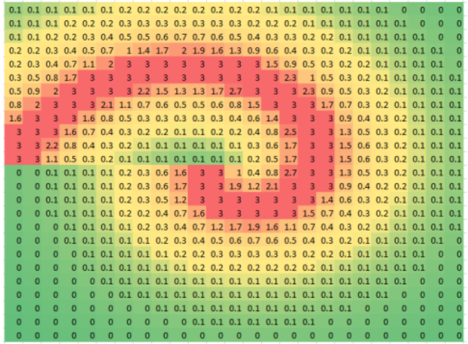
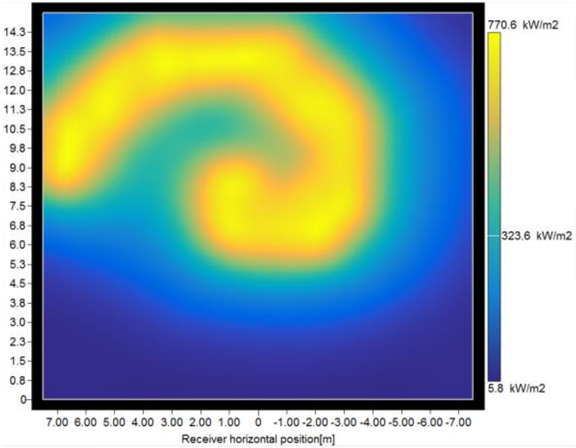
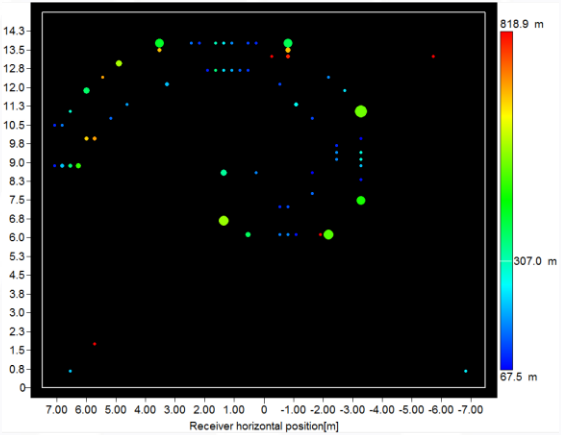
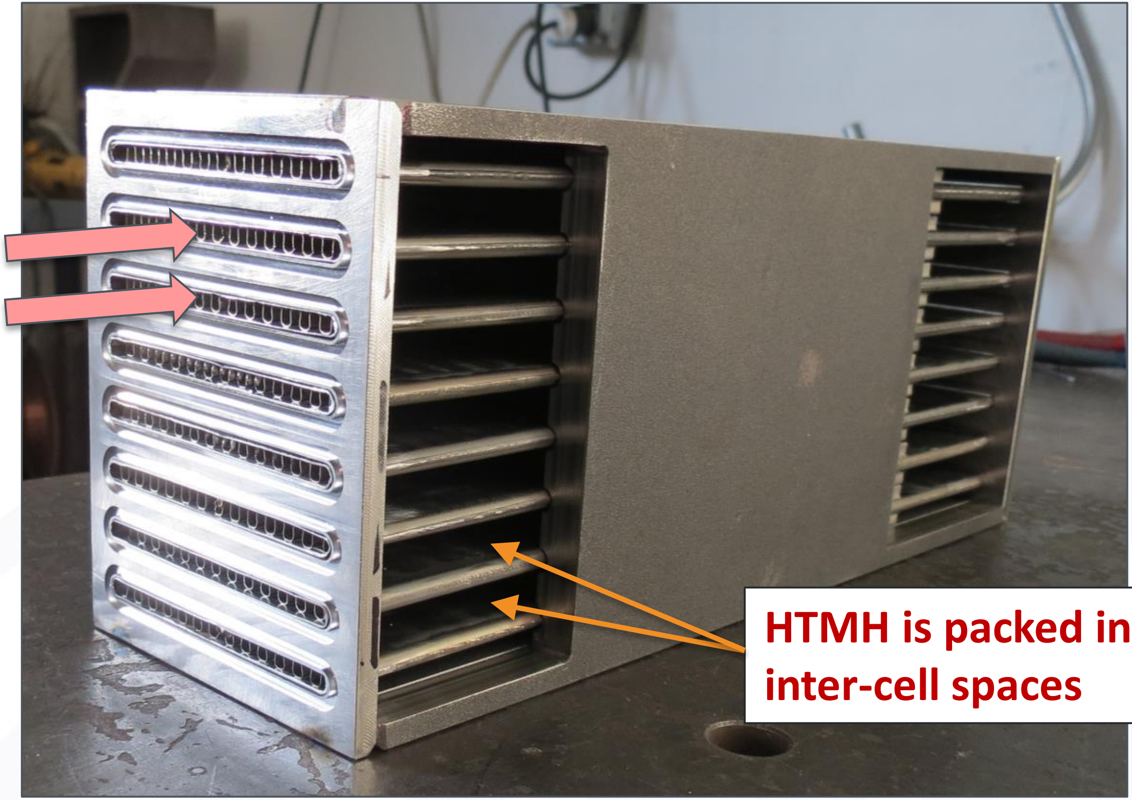




The "image size priority" aimpoint strategy previously implemented in SolarPILOT generates an approximately uniform flux profile by placing reflected heliostat images on the receiver in order of size from largest image to smallest, all the while filling in lower flux regions with heliostat images. The method is relatively simple in that it identifies candidate aim points by comparing local flux density to average flux density and selecting a point that is least illuminated in comparison to other points. In essence, this strategy compares local flux density to an averaged uniform value and selects the point that exhibits the greatest deviation from the target mean value as the next aim point.



Metal Hydride Heat Exchanger



HTF flows within internally-supported and heat-transfer enhanced cells

HTMH is packed in inter-cell spaces

HEX, Receiver Manufacturing/Costs