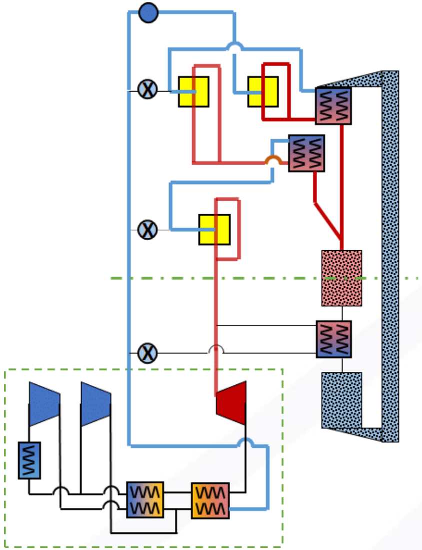
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
SOLAR ENERGY TECHNOLOGIES OFFICE

SETO CSP Program Summit 2019

Gen3 Gas Phase System Development & Demonstration

Panel Discussion



BraytonEnergy
BrightSource
BURNS MCDONNELL
DLR
ECHOGEN power systems
NREL NATIONAL RENEWABLE ENERGY LABORATORY
Greg Mehos
Edisun Microgrids
EPRI
SolarDynamics
SolarTAC Technology Acceleration Center
SOLEX THERMAL SCIENCE
Southwest Solar Technology LLC
WISCONSIN UNIVERSITY OF WISCONSIN-MADISON

Award # DE-EE0008368

19 March 2019

Shaun Sullivan, Principal Engineer, R&D Program Manager

Overview

- **Technical Challenge**: *Gas Circulation*
    - **Solution**: *integrated cycle*
- **Technical Challenge**: *Multi-Pass Heat Addition*
    - **Solution**: *multiple-aimpoint solar field*
- **Risk Retirement**:
    - **Leading up to Phase 3 …**

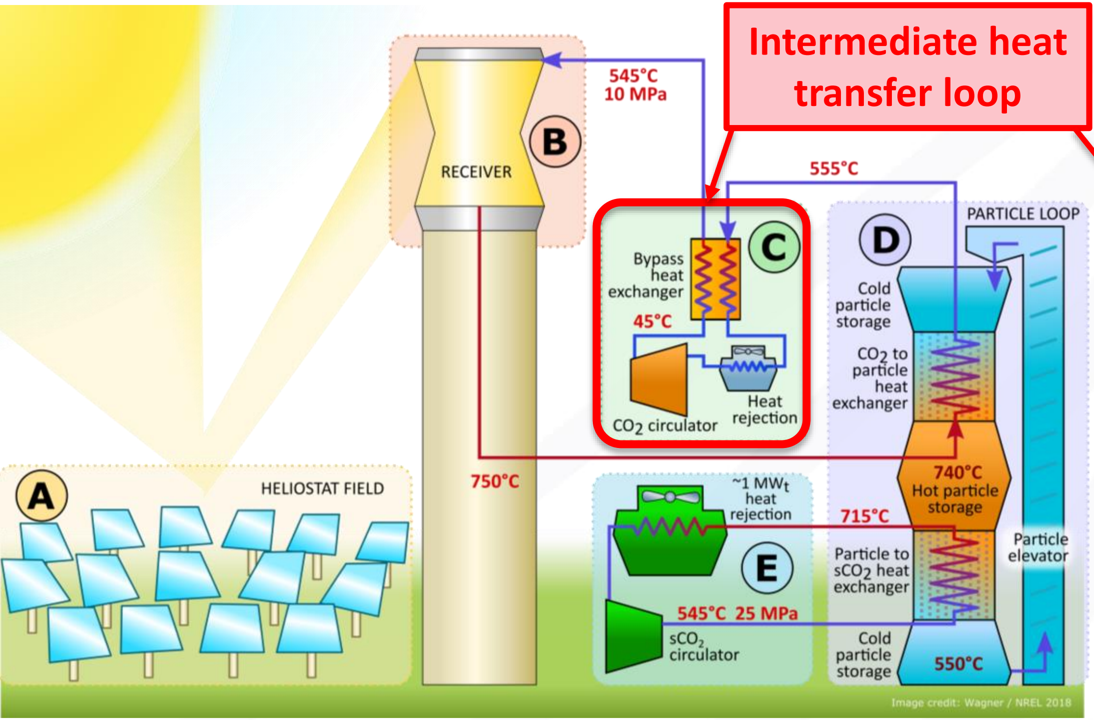
… and in Phase 3 Test Facility

Snapshot

PROJECT NAME	Gen3 Gas Phase System Development and Demonstration
FUNDING OPPORTUNITY	DE-FOA-0001697 Gen3 Concentrating Solar Power Systems Topic Area 1 - Integrated Gen3 Systems
PRINCIPAL INVESTIGATOR	Shaun Sullivan
LEAD ORGANIZATION	Brayton Energy, LLC
PROJECT PARTNERS	NREL, Brightsource, Burns & McDonnell, DLR, Echogen, Edisun Microgrids, EPRI, Greg Mehos, SolarDynamics, SolarTAC, SOLEX, Southwest Solar Technologies, University of Wisconsin
PROJECT DURATION	24 months
BUDGET (DoE/Cost Share)	$9,463,197 ($ 7,570,647 / $ 1,892,550)

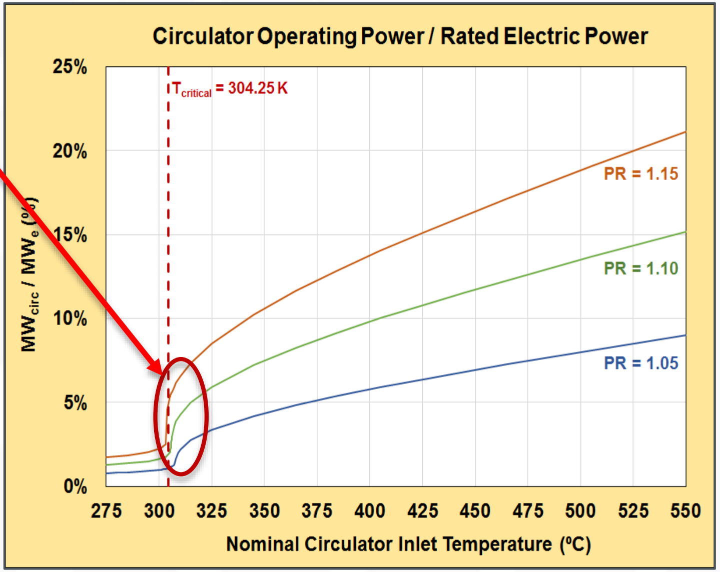
- Employ a gas-phase [supercritical] fluid in the receiver
- Store energy as sensible temperature rise in solid particles
  - Using flowing bed particle-to-sCO_2 heat exchangers

Original Gas Circulation Concept



Intermediate heat transfer loop

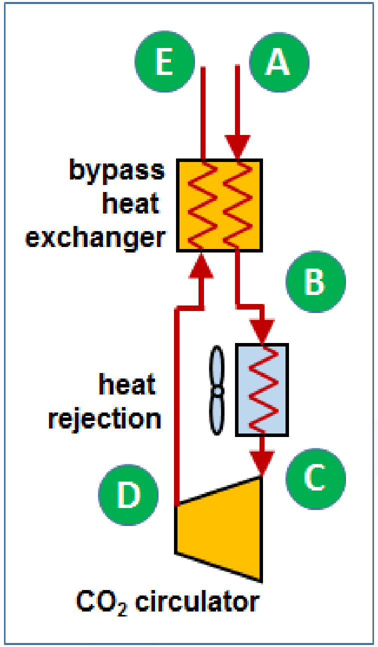
Image credit: Wagner / NREL 2018



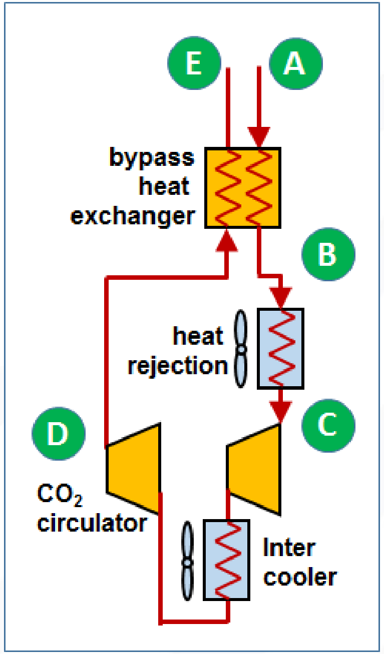
- Leverage the low work of compression near the critical point to minimize circulator parasitic power

Circulator Layout Study

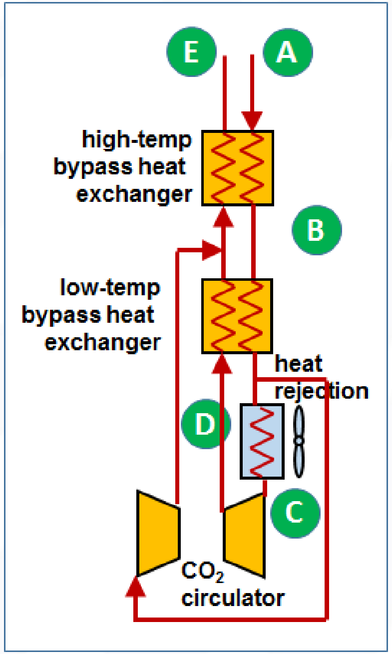
COLD CIRCULATOR



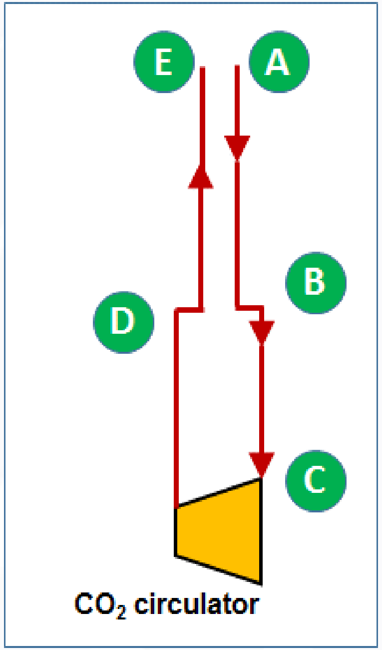
INTERCOOLED CIRC.



RCBC CIRCULATOR



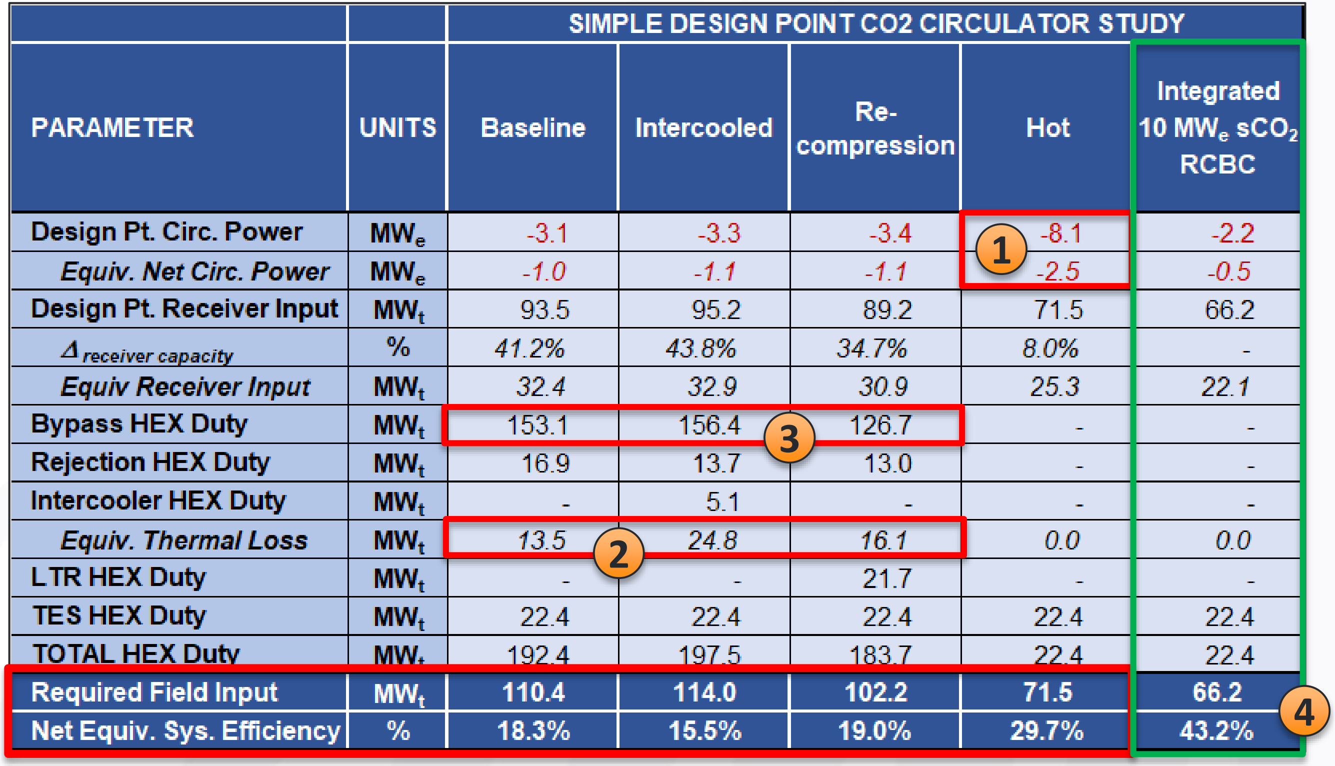
HOT CIRCULATOR



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…



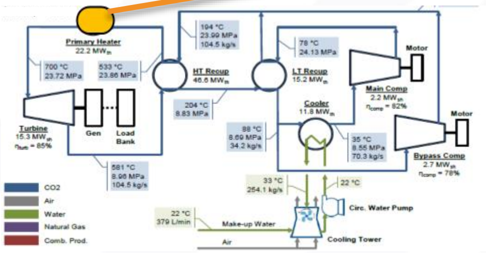
		SIMPLE DESIGN POINT CO2 CIRCULATOR STUDY				
PARAMETER	UNITS	Baseline	Intercooled	Re-compression	Hot	Integrated 10 MW_e sCO_2 RCBC
Design Pt. Circ. Power	MW_e	-3.1	-3.3	-3.4	-8.1	-2.2
Equiv. Net Circ. Power	MW_e	*-1.0*	*-1.1*	*-1.1*	*-2.5*	*-0.5*
Design Pt. Receiver Input	MW_t	93.5	95.2	89.2	71.5	66.2
$\Delta_{receiver\ capacity}$	%	*41.2%*	*43.8%*	*34.7%*	*8.0%*	-
Equiv Receiver Input	MW_t	*32.4*	*32.9*	*30.9*	*25.3*	*22.1*
Bypass HEX Duty	MW_t	153.1	156.4	126.7	-	-
Rejection HEX Duty	MW_t	16.9	13.7	13.0	-	-
Intercooler HEX Duty	MW_t	-	5.1	-	-	-
Equiv. Thermal Loss	MW_t	*13.5*	*24.8*	*16.1*	*0.0*	*0.0*
LTR HEX Duty	MW_t	-	-	21.7	-	-
TES HEX Duty	MW_t	22.4	22.4	22.4	22.4	22.4
TOTAL HEX Duty	MW_t	192.4	197.5	183.7	22.4	22.4
Required Field Input	MW_t	**110.4**	**114.0**	**102.2**	**71.5**	**66.2**
Net Equiv. Sys. Efficiency	%	**18.3%**	**15.5%**	**19.0%**	**29.7%**	**43.2%**

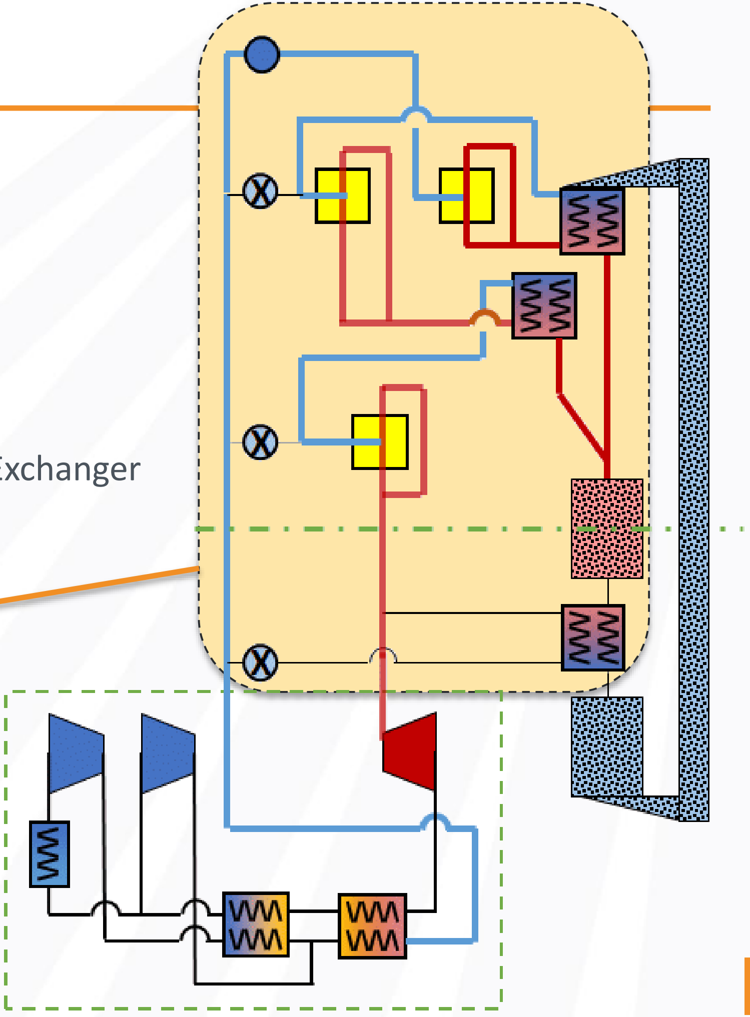
Values shown are for design point, normalized to a 10 MW_e STEP-like sCO_2 RCBC system with 13 hours of storage

Integrated sCO_2 Power Cycle

- Power block already supplies sCO_2:
  - at the desired temperature,
  - utilizing near-critical compression,
  - with thermal and cycle losses already paid for, and
  - no additional capital cost for circulator, heat exchanger, etc.
- [CSP + Storage] fits within the “black box” of the Primary Heat Exchanger
  - Flow is returned to the power block at the desired temperature
  - Changes in operating states manifest only as variations in the PHX ΔP

PARAMETER	UNITS	VALUES
Equiv. Net Power	MW_e	9.54
Equiv. Receiver Input	MW_t	22.09
Max. Tot. Rec. Input	MW_t	66.20
Equiv. Net Efficiency	%	43.2%

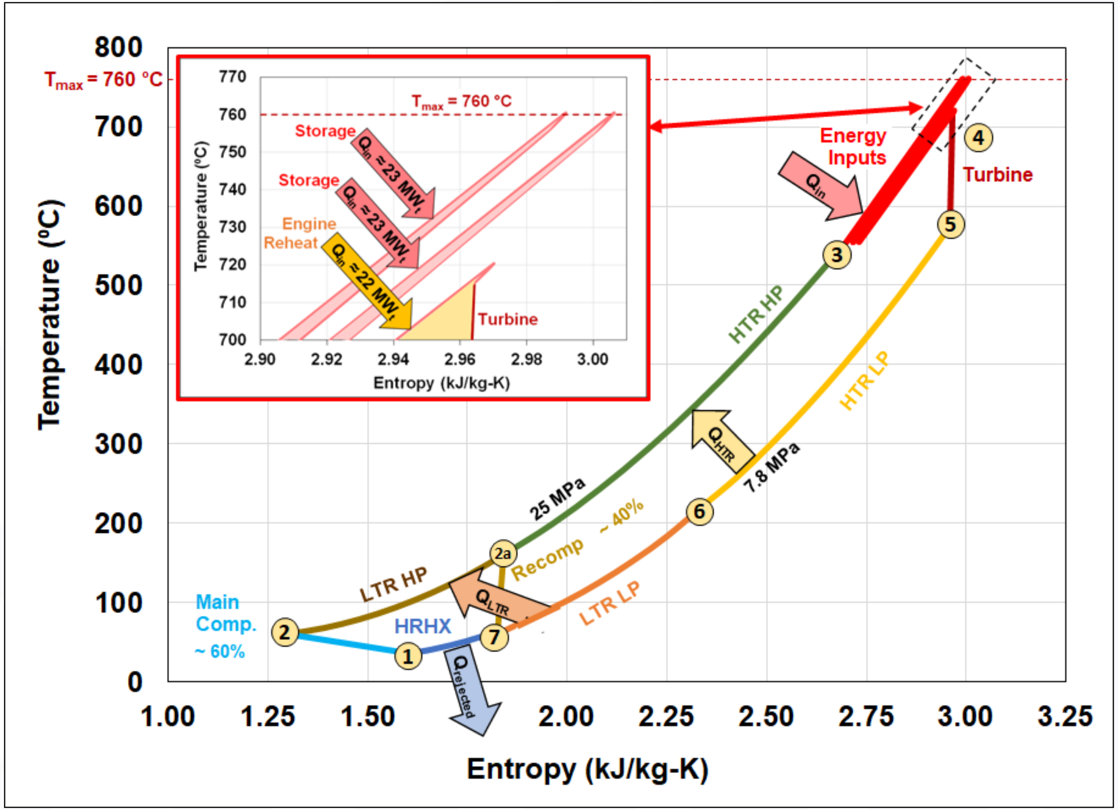




Implications of the coupled system …

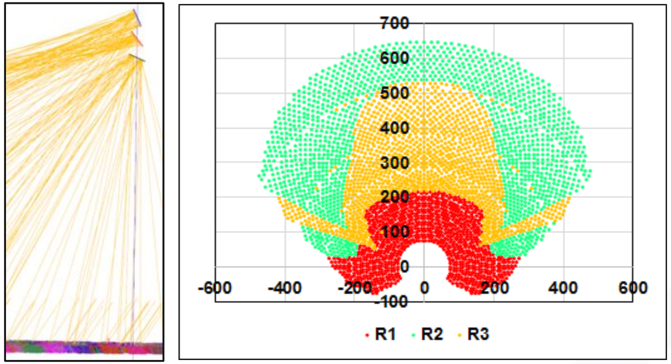
Because the receiver and PHX thermal duty is constrained by (a) the flow rate of the power block and (b) the nominal PHX ΔT, energy collection is limited to ~ 23 $\mathrm{MW_t}$

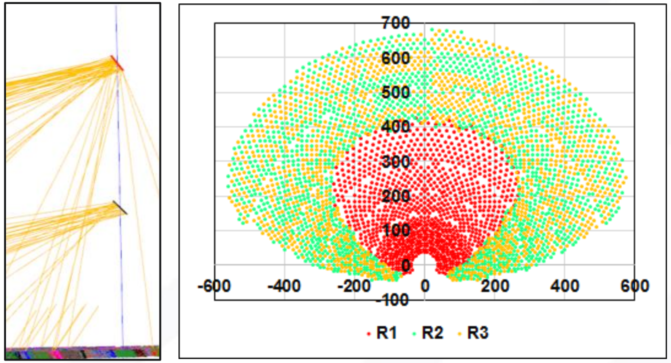
- To achieve higher rates of storage, multiple [receiver + TES] passes are employed



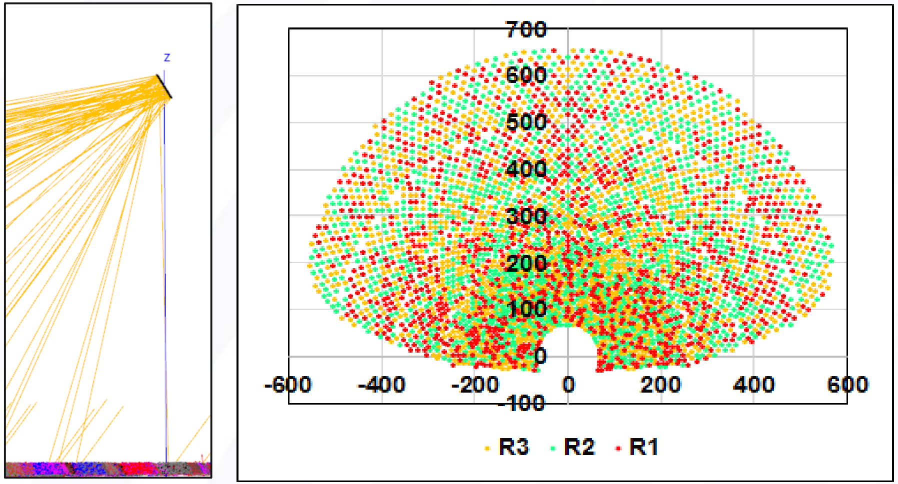
Multiple Receiver Optimization

M. Wagner





- SolarPILOT modified to enable cost minimization including new variables:
  - Multiple receivers (height, angle, size, etc.)
  - Cost of integrated code-case piping for sCO_2



Gen3 Risk Retirement

1. Because the HTF is not used as the thermal storage media, the gas-phase system must economically minimize multiple HX approach temperatures:
   - Receiver (ΔT between hot solar absorber wall → warm sCO_2 HTF)
   - TES HX, charging (ΔT between hot sCO_2 HTF → warm TES particles)
   - TES HX, discharging (ΔT between hot TES particles → warm sCO_2 engine working fluid)

   Meeting target approach temperatures is key to the system performance

2. Size, durability, and performance of high-temperature sCO_2 components – particularly the receiver and TES heat exchanger – is critical

Receiver Risk Retirement (P1 & P2)

- **Phase 1**
  - Subcomponent (cell) level testing
    - Performance (f, j) testing
    - Creep life
    - Fatigue life
    - Peak flux durability

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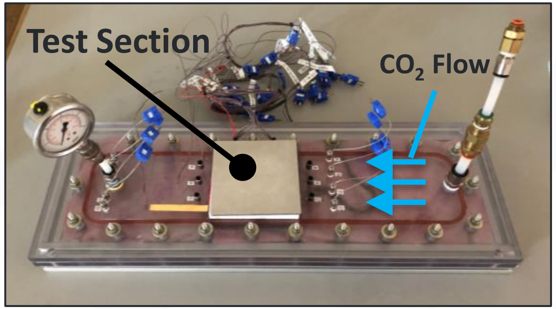
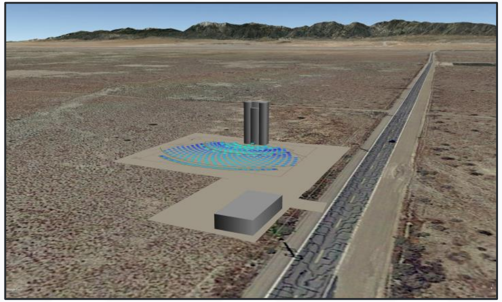
- **Phase 2**
  - Assembly level testing
    - On-sun 100 kW_t receiver subsection testing

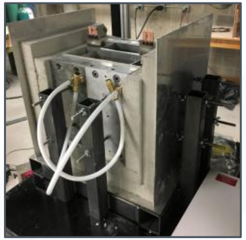
SolarTAC Technology Acceleration Center

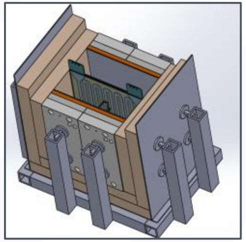


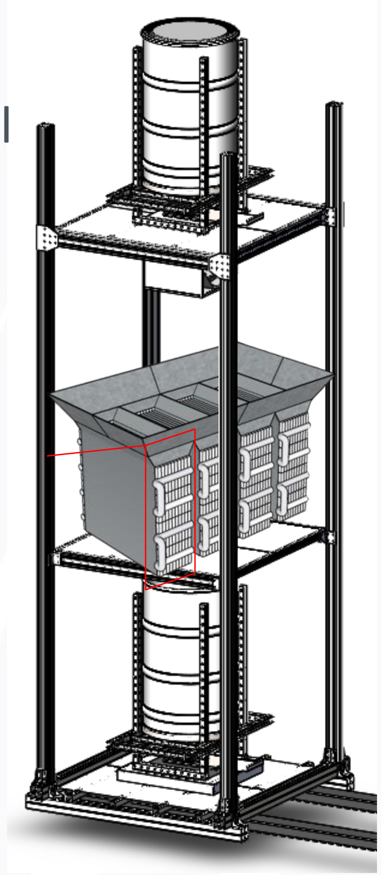


TES Heat Exchanger Risk Retirement (P1 & P2)

- **Phase 1**
  - Modeling Confidence
    - Parallel independent HEX develop.
  - Particle level
    - Mat’l prop. measurements
  - Subcomponent level testing
    - Performance (f, j)
    - Creep life
    - Fatigue life
- **Phase 2**
  - Assembly Level
    - TES particle-to-sCO$_2$ heat exchanger perf. testing

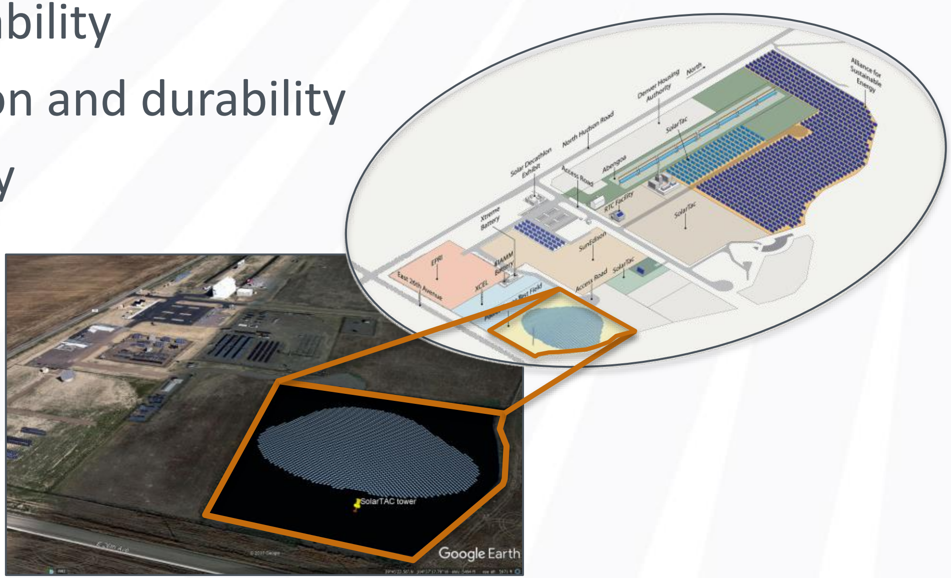






Phase 3 Test Facility: Critical Risk Retirement

- Proof of system manufacturability
- Megawatt-scale integrated system operation
  - Receiver operation and durability
  - TES heat exchanger operation and durability
  - Round-trip storage efficiency
  - Integrated system performance and flexibility



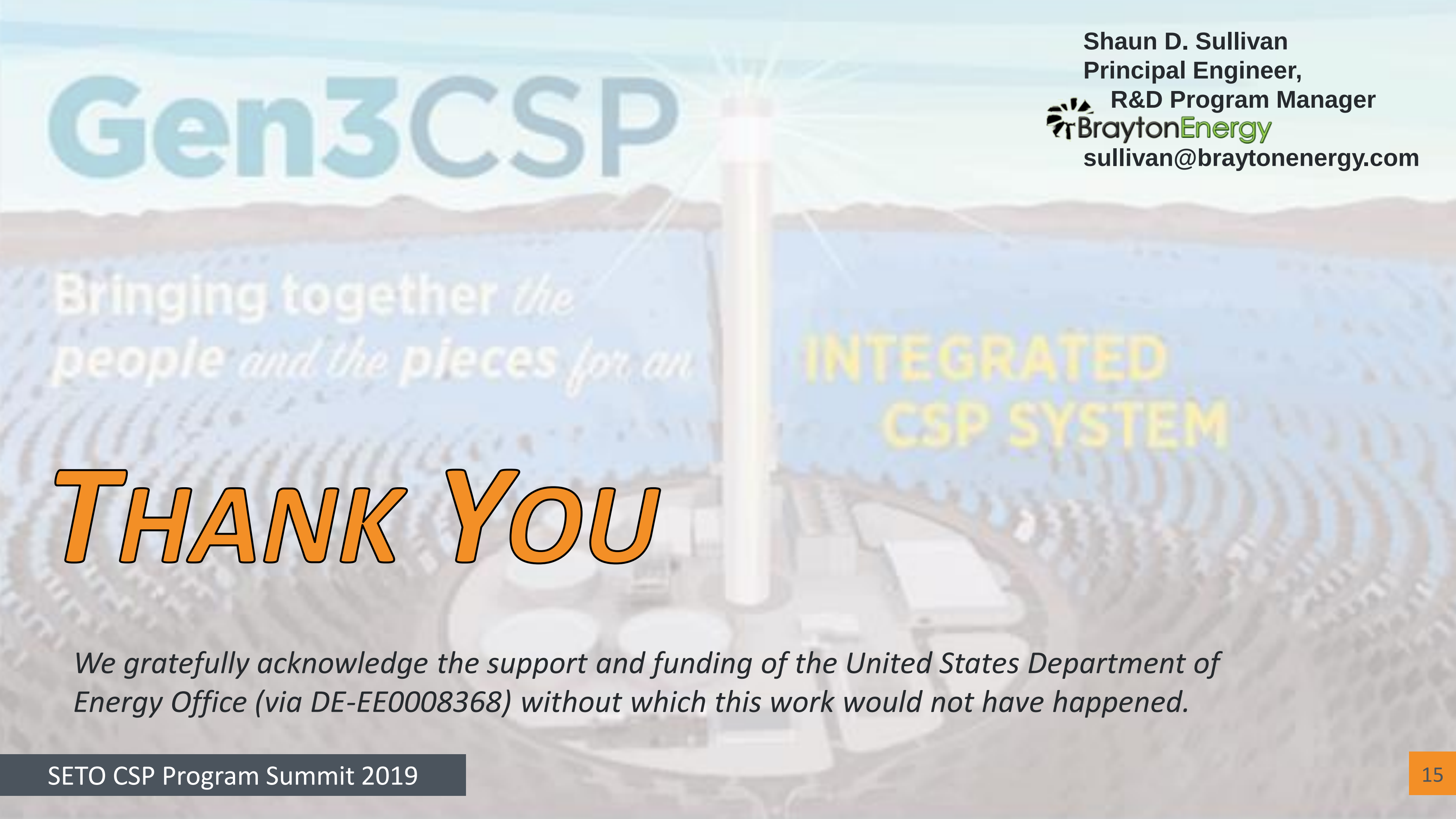
Commercialization

Anticipated Challenges …

- sCO_2 cycle uncertainty:
  - off-design conditions;
    - Ambient temperature
    - Power turndown
- Identifying commercial scale:
  - Larger, familiar systems (> 50 MW_e)
    - with high capital cost and long development times
  - Smaller, more modular systems (e.g. 10 MW_e, 9-12 month installation)

… and Near-Term Opportunities

- [CSP+storage] with air-Brayton cycles
  - Higher temperature / good efficiency
  - Low risk, very mature technology
  - Low-cost
  - Low barriers to adoption (familiar)



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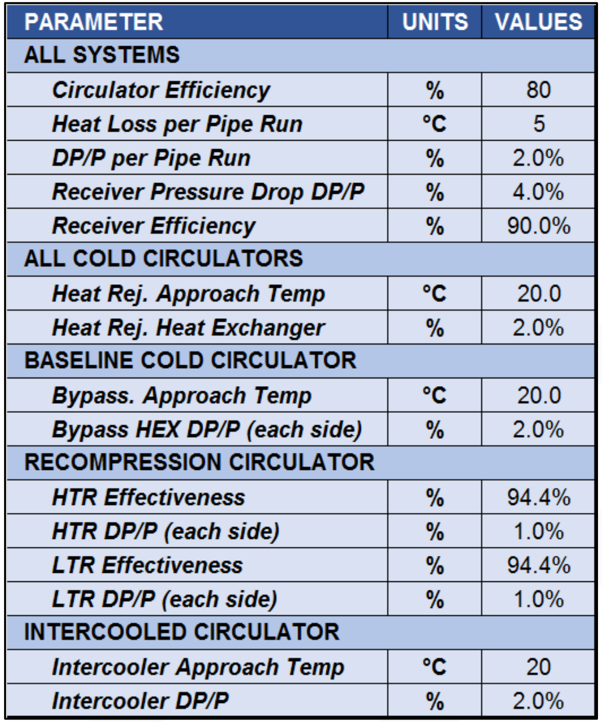
THANK YOU

We gratefully acknowledge the support and funding of the United States Department of Energy Office (via DE-EE0008368) 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

Integrated System Operation

OPERATING MODE	HOURS PER DAY	RECEIVER ENERGY (MWh)	STORAGE ENERGY (MWh)	DISCHARGE ENERGY (MWh)	ENERGY (MWh)
R3/Fd0/D0	6	397.2	273.4	0.0	46.5
R2/Fd0/D0	1	44.3	22.8	0.0	9.0
R1/Fd0/D0	1	22.3	0.0	0.0	10.0
R0/Fd1/D0	13	0.0	0.0	296.9	134.8
TOTAL		463.8	296.2	296.9	200.4
				Daily Thermal Efficiency	**43.2%**

# of Receivers Used

Fraction of Flow to Discharge HX

De-Rate Fraction of Engine

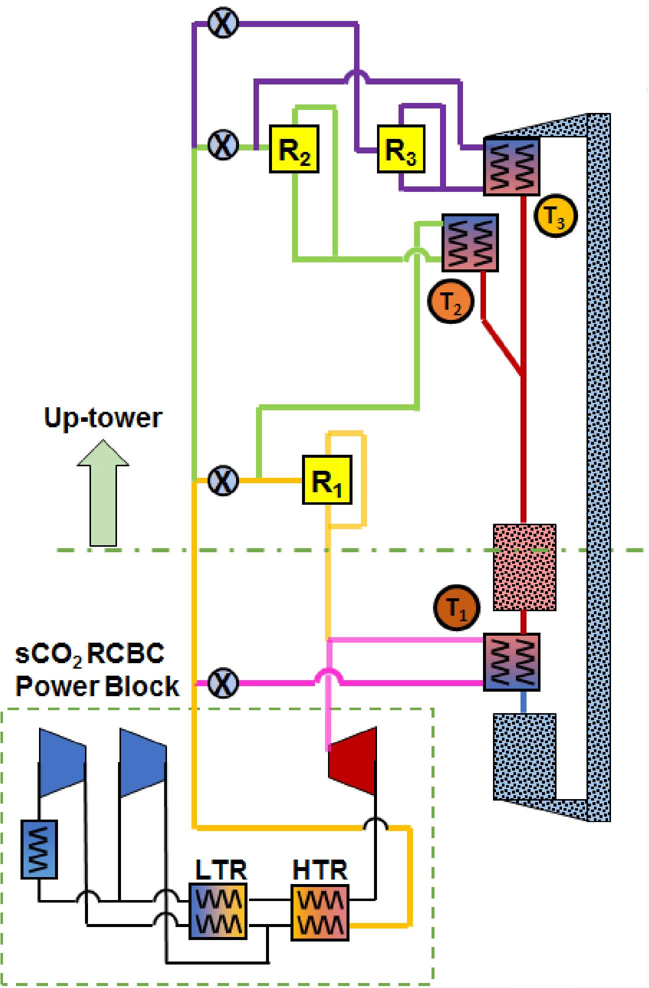
R3/Fd0/D0

🟪 R3/Fd0/D0

🟩 R2/Fd0/D0

🟨 R1/Fd0/D0

🟥 R0/Fd1/D0



Full Integrated System Operating Map

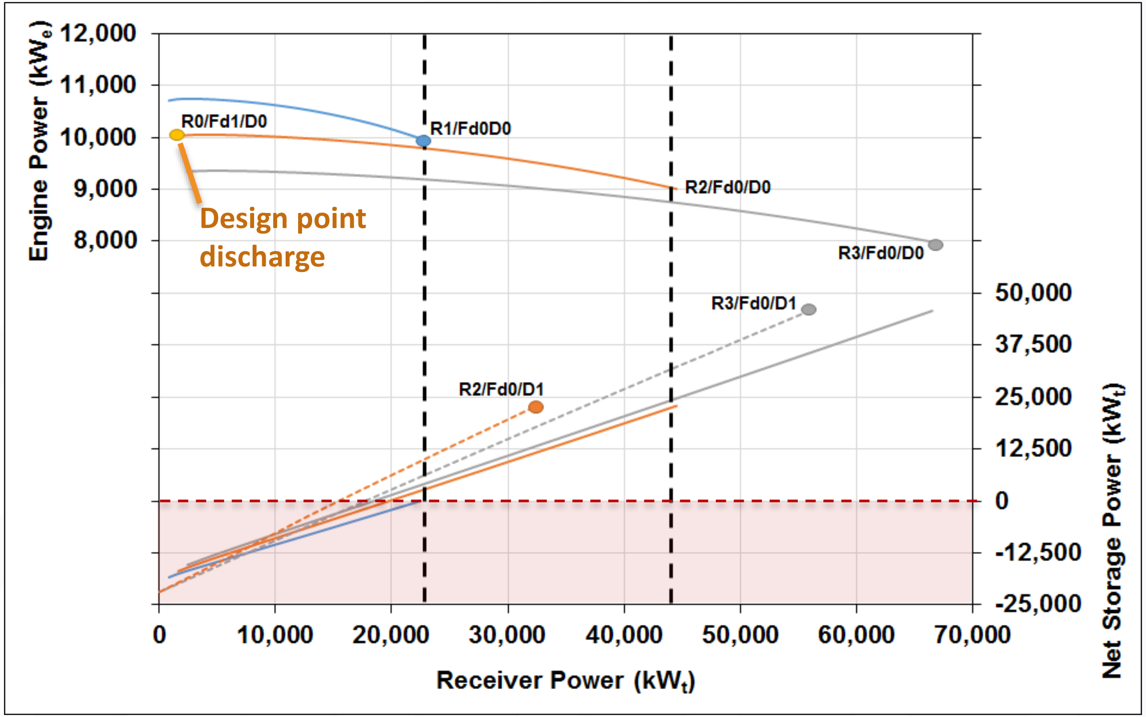
- **TOP**: Net power generation
- **BOTTOM**: Net energy storage
  - Red indicates discharge

# of Receivers Used

Fraction of Flow to Discharge HX

De-Rate Fraction of Engine

R3/Fd0/D0



1.2.1 – Solar Modeling Details

- Heliostats:
  - 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
- Tower Costs:
  - WithOUT piping:

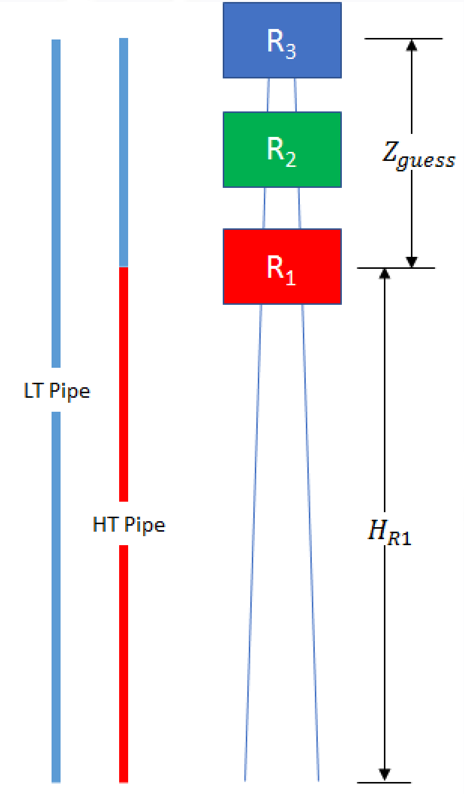
$$c_{tower} = c_{fixed} e^{A(H_{R1}+Z_{guess})}$$

  - With piping: (no connection distances included)

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

SolarPILOT form:

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



1.2.2 – Field Modeling: Multiple Aimpoint

M. Wagner

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

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

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

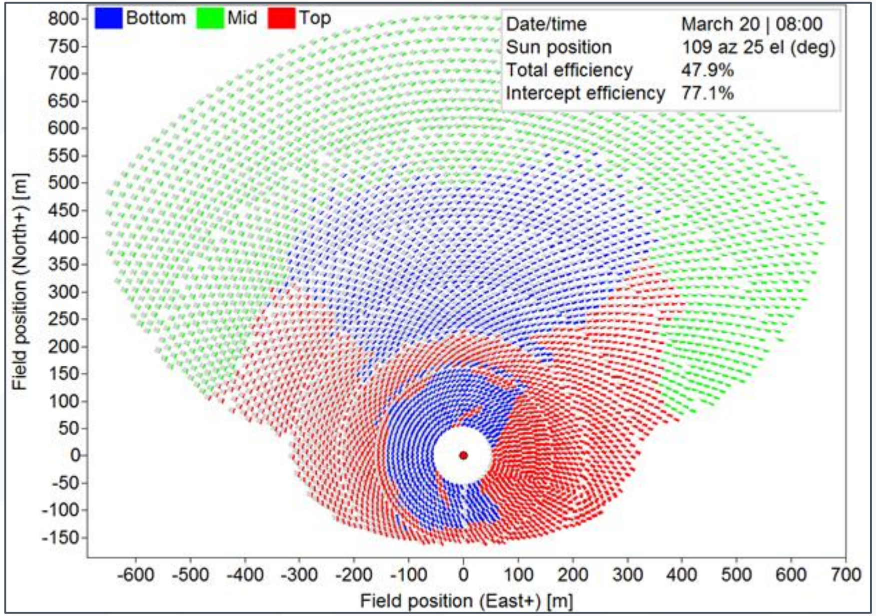
1.2.2 – Field Modeling: Multiple Aimpoint

Case:

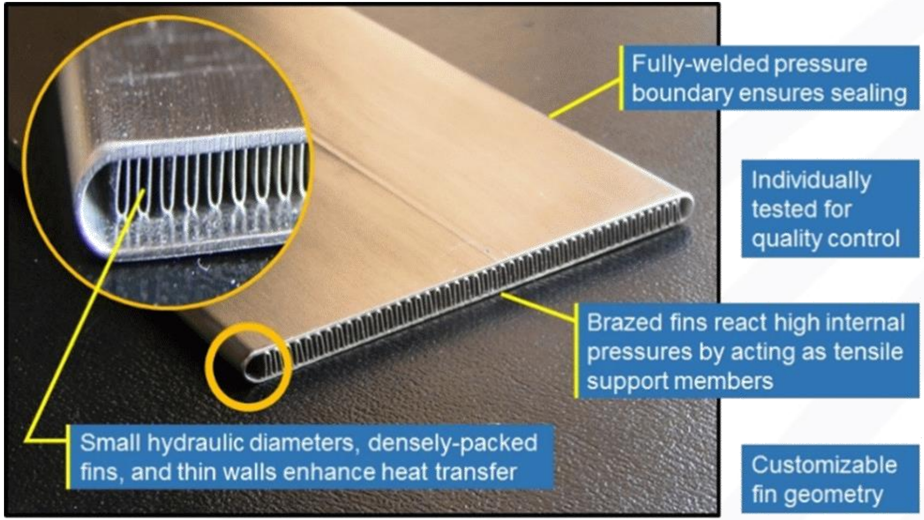
- Optimized system, uniform power among 3 receivers
- Aimpoint map shown for equinox, summer & winter solstices

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



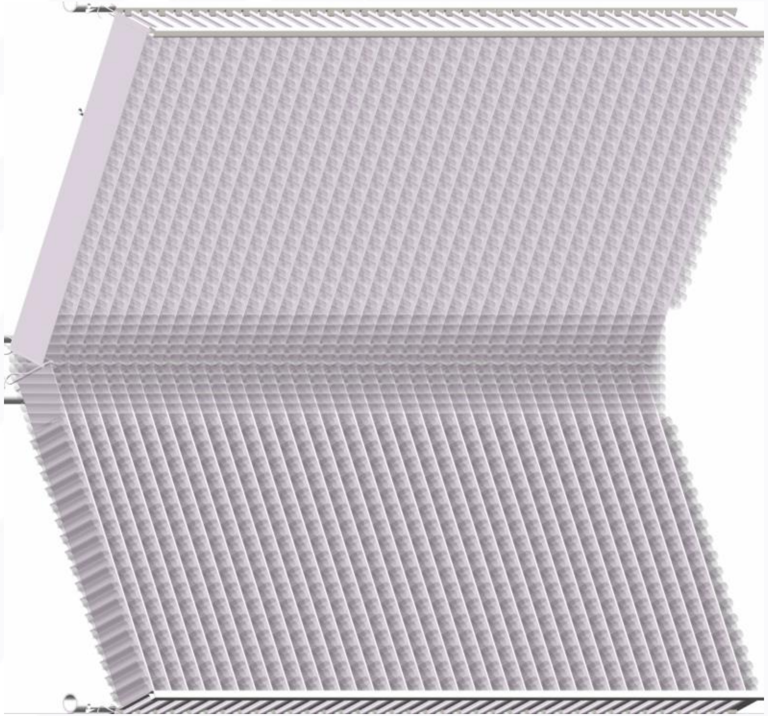
Fully-welded pressure boundary ensures sealing

Individually tested for quality control

Brazed fins react high internal pressures by acting as tensile support members

Small hydraulic diameters, densely-packed fins, and thin walls enhance heat transfer

Customizable fin geometry



1.2.2 – Field Modeling: Flux Profiling

M. Wagner

Premise:

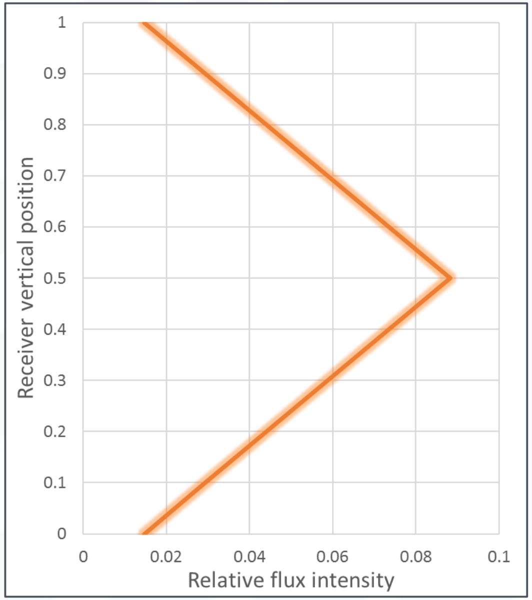
- Advanced receivers at high temperature require unique incident flux patterns to maintain allowable surface temperature

Goal:

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

Current capability:

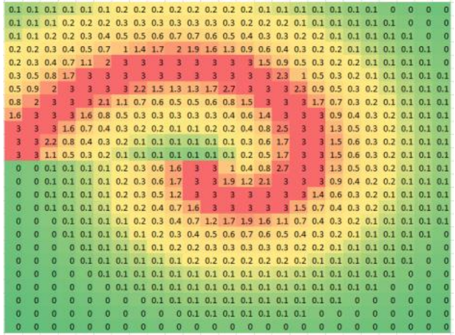
- Enforce uniform flux using iterative approach, assign aimpoints using random distributions, or use simple aim points and process using dedicated programs



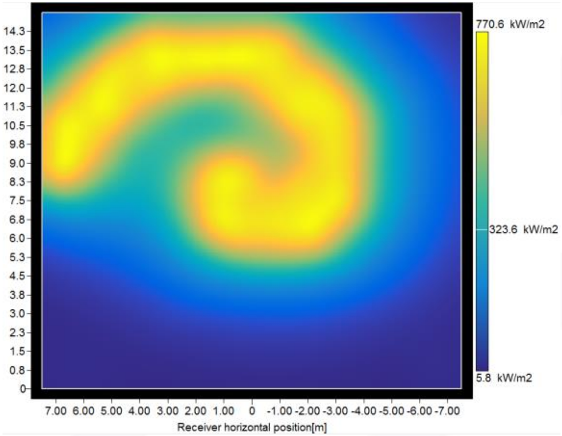
Desired flux profile for the gas receiver. The highest intensity flux is near the vertical midpoint with reduced intensity near the edges

1.2.2 – Flux Profiling

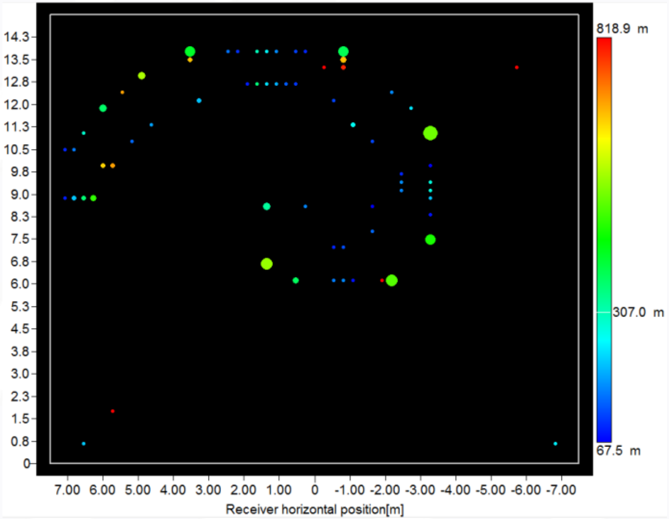
M. Wagner



0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0	0
0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0
0.1	0.1	0.2	0.2	0.3	0.4	0.5	0.5	0.6	0.7	0.7	0.6	0.5	0.4	0.3	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0	0
0.2	0.2	0.3	0.4	0.5	0.7	1	1.4	1.7	2	1.9	1.6	1.3	0.9	0.6	0.4	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0
0.2	0.3	0.4	0.7	1.1	2	3	3	3	3	3	3	3	3	1.5	0.9	0.5	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0
0.3	0.5	0.8	1.7	3	3	3	3	3	3	3	3	3	3	3	2.3	1	0.5	0.3	0.2	0.1	0.1	0.1	0.1	0.1
0.5	0.9	2	3	3	3	3	2.2	1.5	1.3	1.3	1.7	2.7	3	3	3	2.3	0.9	0.5	0.3	0.2	0.1	0.1	0.1	0.1
0.8	2	3	3	3	2.1	1.1	0.7	0.6	0.5	0.5	0.6	0.8	1.5	3	3	3	1.7	0.7	0.3	0.2	0.1	0.1	0.1	0.1
1.6	3	3	3	1.6	0.8	0.5	0.3	0.3	0.3	0.3	0.3	0.4	0.6	1.4	3	3	3	0.9	0.4	0.3	0.2	0.1	0.1	0.1
3	3	3	1.6	0.7	0.4	0.3	0.2	0.2	0.1	0.1	0.2	0.2	0.4	0.8	2.5	3	3	1.3	0.5	0.3	0.2	0.1	0.1	0.1
3	3	2.2	0.8	0.4	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.6	1.7	3	3	1.5	0.6	0.3	0.2	0.1	0.1	0.1
3	3	1.1	0.5	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.5	1.7	3	3	1.5	0.6	0.3	0.2	0.1	0.1	0.1
0	0	0.1	0.1	0.1	0.1	0.2	0.3	0.6	1.6	3	3	1	0.4	0.8	2.7	3	3	1.3	0.5	0.3	0.2	0.1	0.1	0.1
0	0	0.1	0.1	0.1	0.1	0.2	0.3	0.6	1.7	3	3	1.9	1.2	2.1	3	3	3	0.9	0.4	0.2	0.2	0.1	0.1	0.1
0	0	0.1	0.1	0.1	0.1	0.2	0.3	0.5	1.2	3	3	3	3	3	3	3	1.4	0.6	0.3	0.2	0.1	0.1	0.1	0.1
0	0	0.1	0.1	0.1	0.1	0.2	0.2	0.4	0.7	1.6	3	3	3	3	3	1.5	0.7	0.4	0.3	0.2	0.1	0.1	0.1	0.1
0	0	0	0.1	0.1	0.1	0.1	0.2	0.3	0.4	0.7	1.2	1.7	1.9	1.6	1.1	0.7	0.4	0.3	0.2	0.1	0.1	0.1	0.1	0.1
0	0	0	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0
0	0	0	0	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0	0
0	0	0	0	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0	0
0	0	0	0	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0
0	0	0	0	0	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0	0
0	0	0	0	0	0	0	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

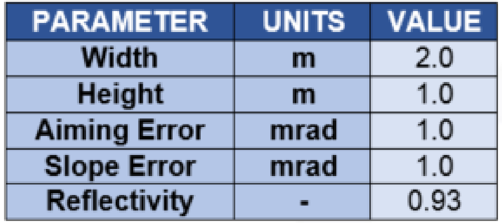


The "image size priority" aimpoint strategy previously implemented in SolarPILOT generates an approximately uniform flux profile by placing reflected heliostat images on the receiver in order of size from largest image to smallest, all the while filling in lower flux regions with heliostat images. The 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.

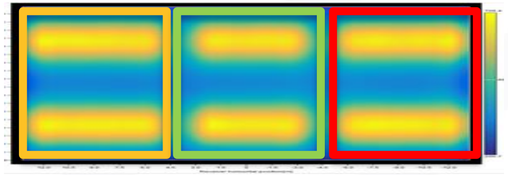


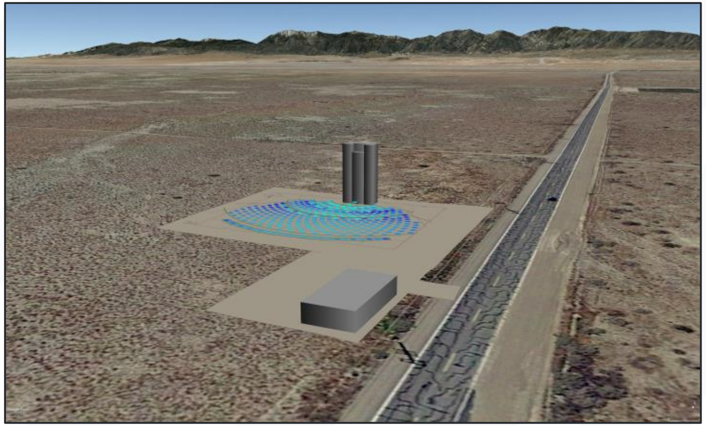
Heliostat Control

- **Phase 1**
  - Performance validation in a solar field application
  - Control code development
- **Phase 2**
  - Flux control validation during on-sun receiver testing



PARAMETER	UNITS	VALUE
Width	m	2.0
Height	m	1.0
Aiming Error	mrad	1.0
Slope Error	mrad	1.0
Reflectivity	-	0.93





TES Heat Exchanger Manufacturing Roadmap

- Commercial PHX anticipated to be 33% under DoE budget