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

SOLAR ENERGY TECHNOLOGIES OFFICE

Next Generation Receivers

R&D Virtual Workshop Series

Concentrating Solar Power Program

Avi Shultz, CSP Program Manager
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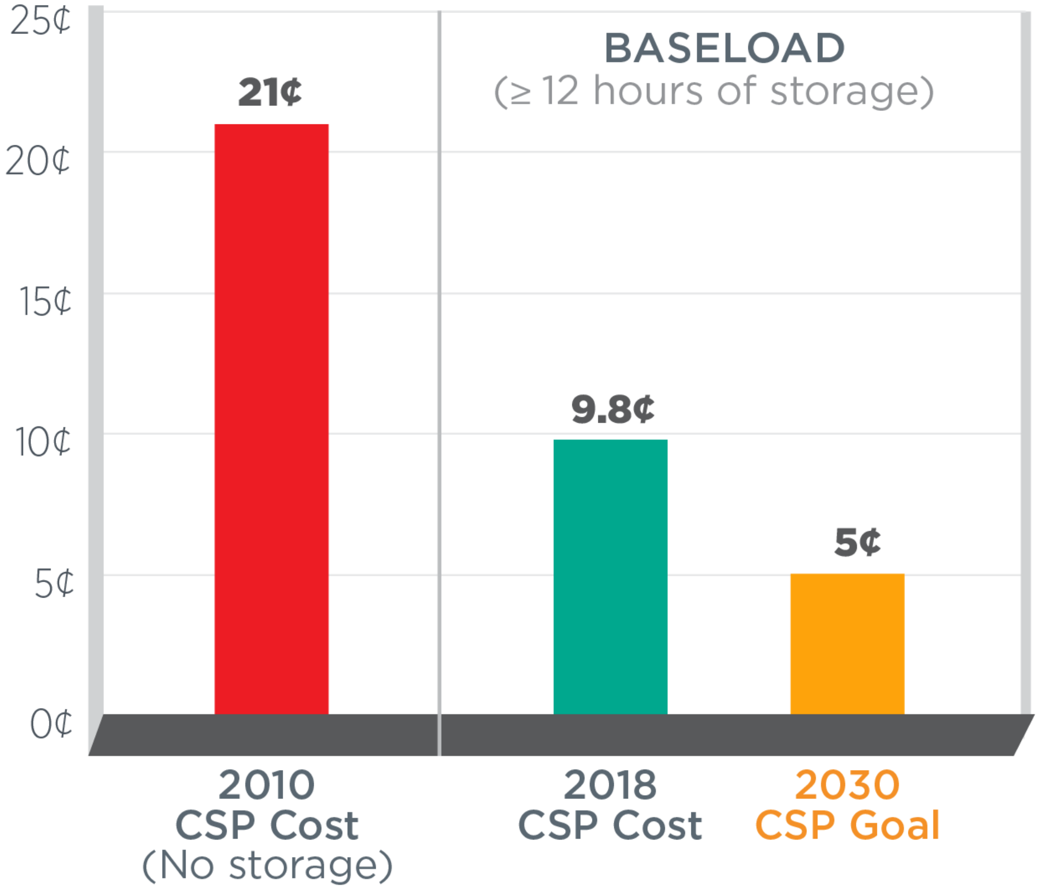
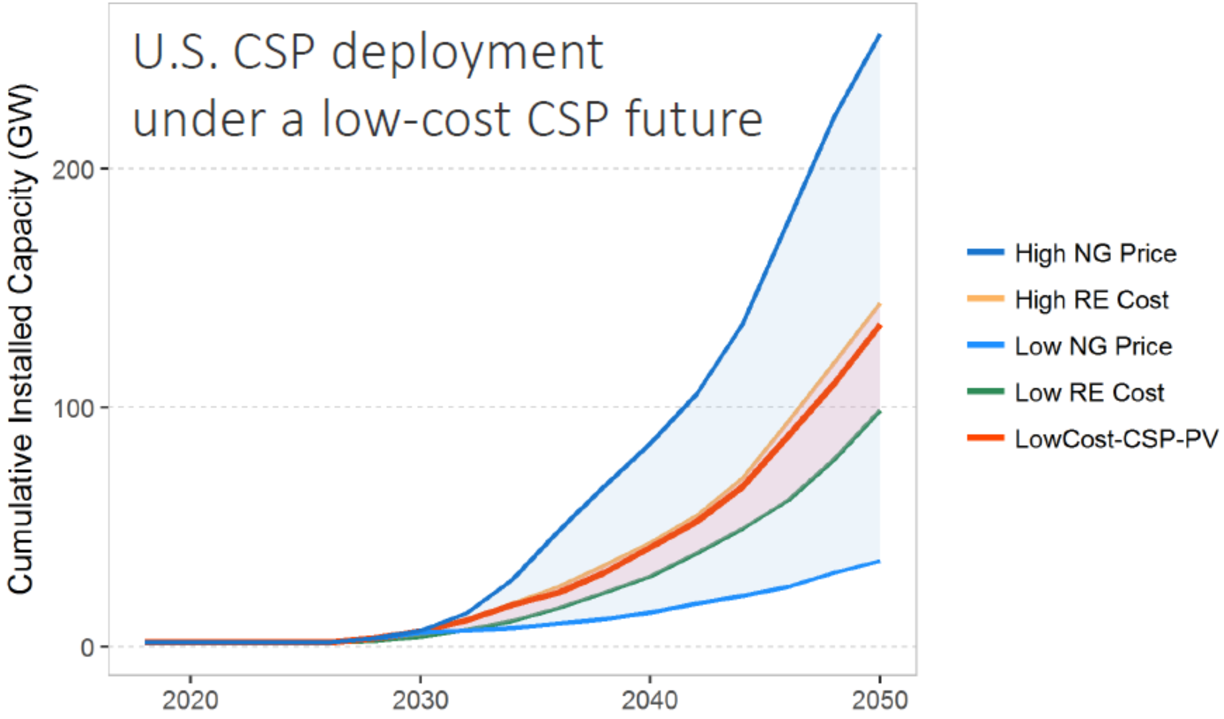
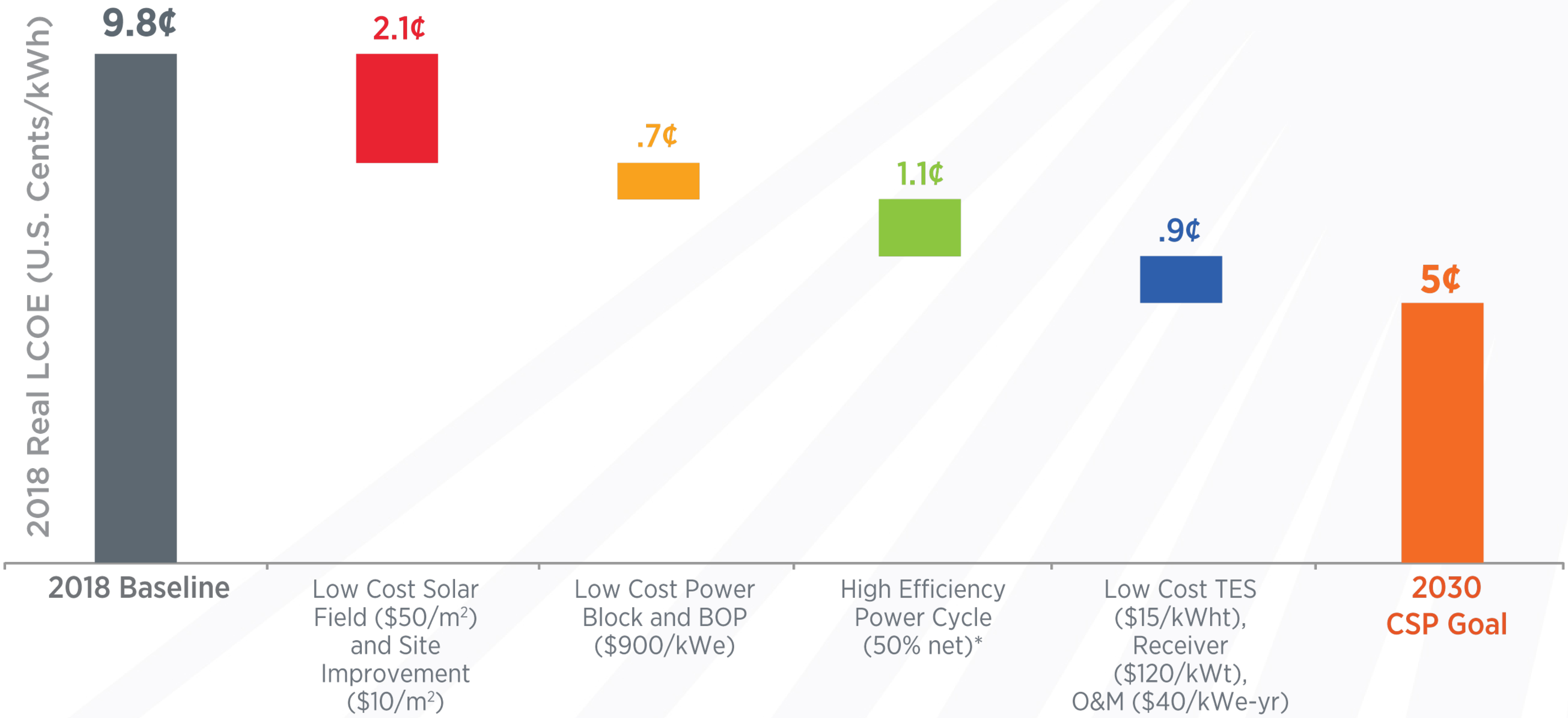
Progress and Goals: 2030 LCOE Goals





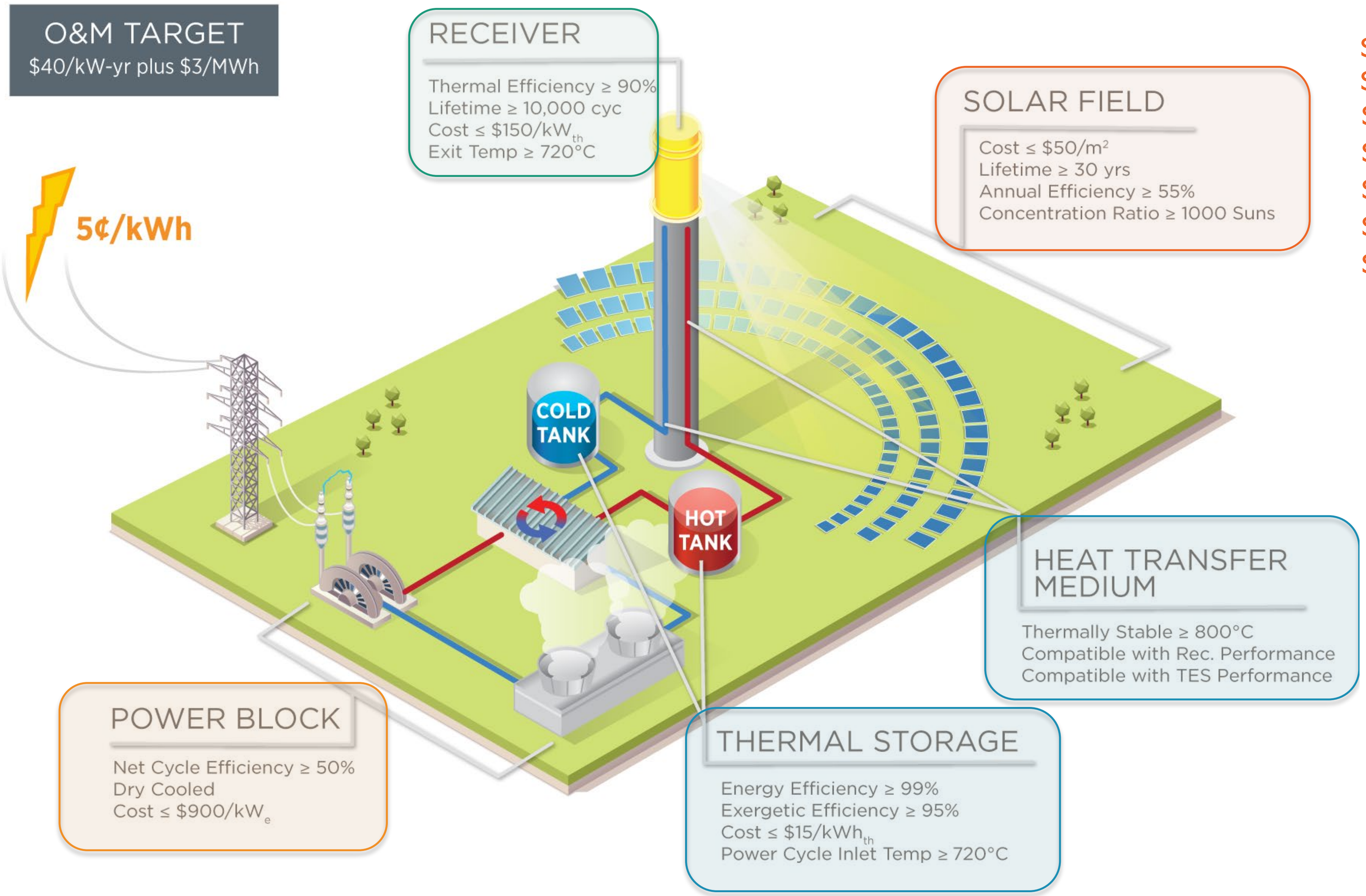
Murphy, et al. **2019**, NREL/TP-6A20-71912

A Pathway to 5 Cents per KWh for Baseload CSP



*Assumes a gross to net conversion factor of 0.9

CSP Technical Targets



O&M TARGET
$40/kW-yr plus $3/MWh

5¢/kWh

RECEIVER
Thermal Efficiency ≥ 90%
Lifetime ≥ 10,000 cyc
Cost ≤ \$150/kW$_{th}$
Exit Temp ≥ 720°C

SOLAR FIELD
Cost ≤ \$50/m^2
Lifetime ≥ 30 yrs
Annual Efficiency ≥ 55%
Concentration Ratio ≥ 1000 Suns

HEAT TRANSFER MEDIUM
Thermally Stable ≥ 800°C
Compatible with Rec. Performance
Compatible with TES Performance

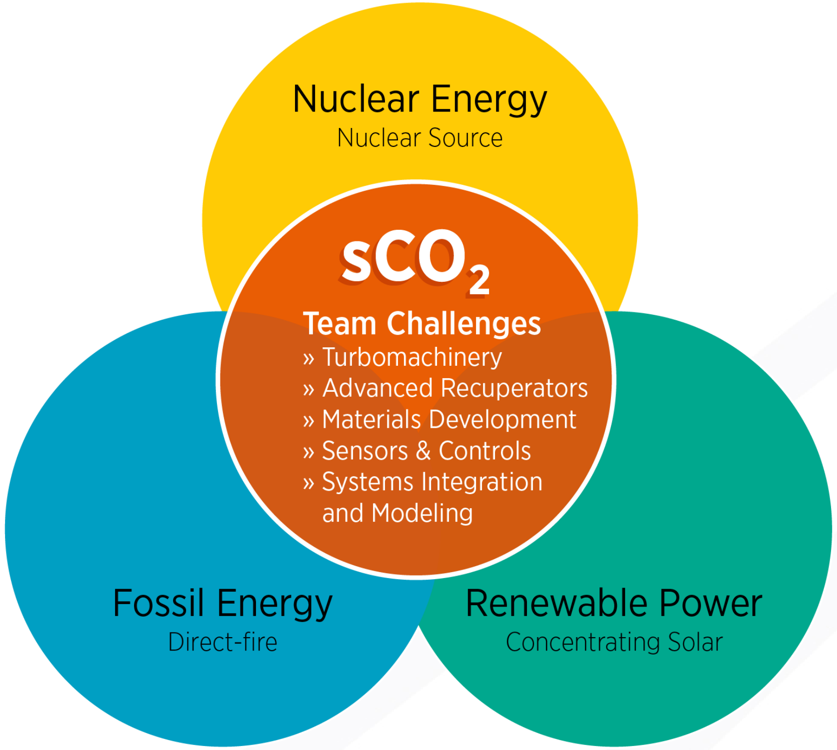
THERMAL STORAGE
Energy Efficiency ≥ 99%
Exergetic Efficiency ≥ 95%
Cost ≤ \$15/kWh$_{th}$
Power Cycle Inlet Temp ≥ 720°C

POWER BLOCK
Net Cycle Efficiency ≥ 50%
Dry Cooled
Cost ≤ \$900/kW$_e$

Competitive Programs

$43M	FY 2020 SETO FOA (2020)
$30M	FY 2019 SETO FOA (2019)
$22M	FY 2018 SETO FOA (2019)
$21M	Solar Desalination (2018)
$22M	FY19-21 National Lab Call (2018)
$70M	Gen3 CSP Systems (2018)
$15M	Gen3 CSP Lab Support (2018)
$9M	COLLECTS (2016)
$32M	CSP: APOLLO (2015)
$29M	CSP SuNLaMP (2015)
$1.4M	SolarMat II (2014)
$10M	CSP: ELEMENTS (2014)
$1.1M	SunShot Incubator (Recurring)
$4M	PREDICTS (2013)
$2M	SolarMat (2013)
$10M	CSP-HIBRED (2013)
$27M	National Lab R&D (2012)
$10M	SunShot MURI (2012)
$56M	CSP SunShot R&D (2012)
$0.5M	BRIDGE (2012)
$62M	CSP Baseload (2010)

Next Generation CSP will Leverage Next Generation Power Cycles



Nuclear Energy
Nuclear Source

sCO_2

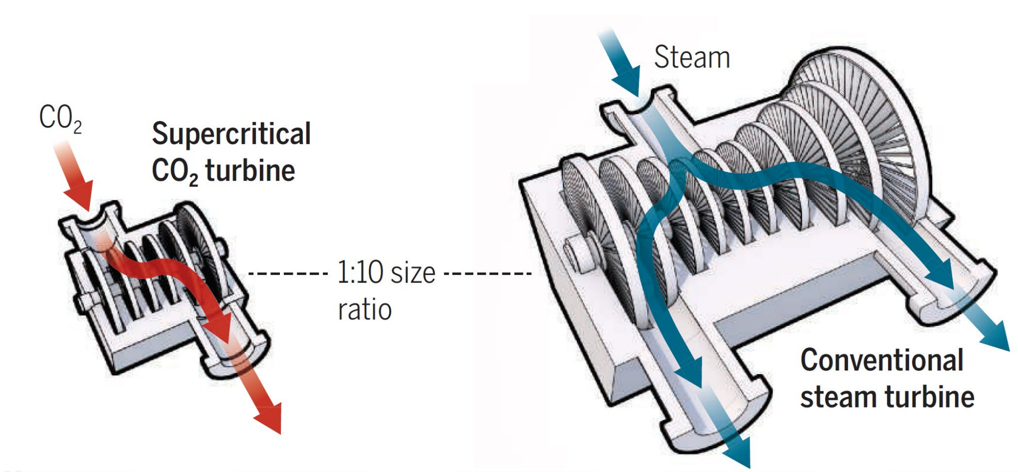
Team Challenges
- » Turbomachinery
- » Advanced Recuperators
- » Materials Development
- » Sensors & Controls
- » Systems Integration and Modeling

Fossil Energy
Direct-fire

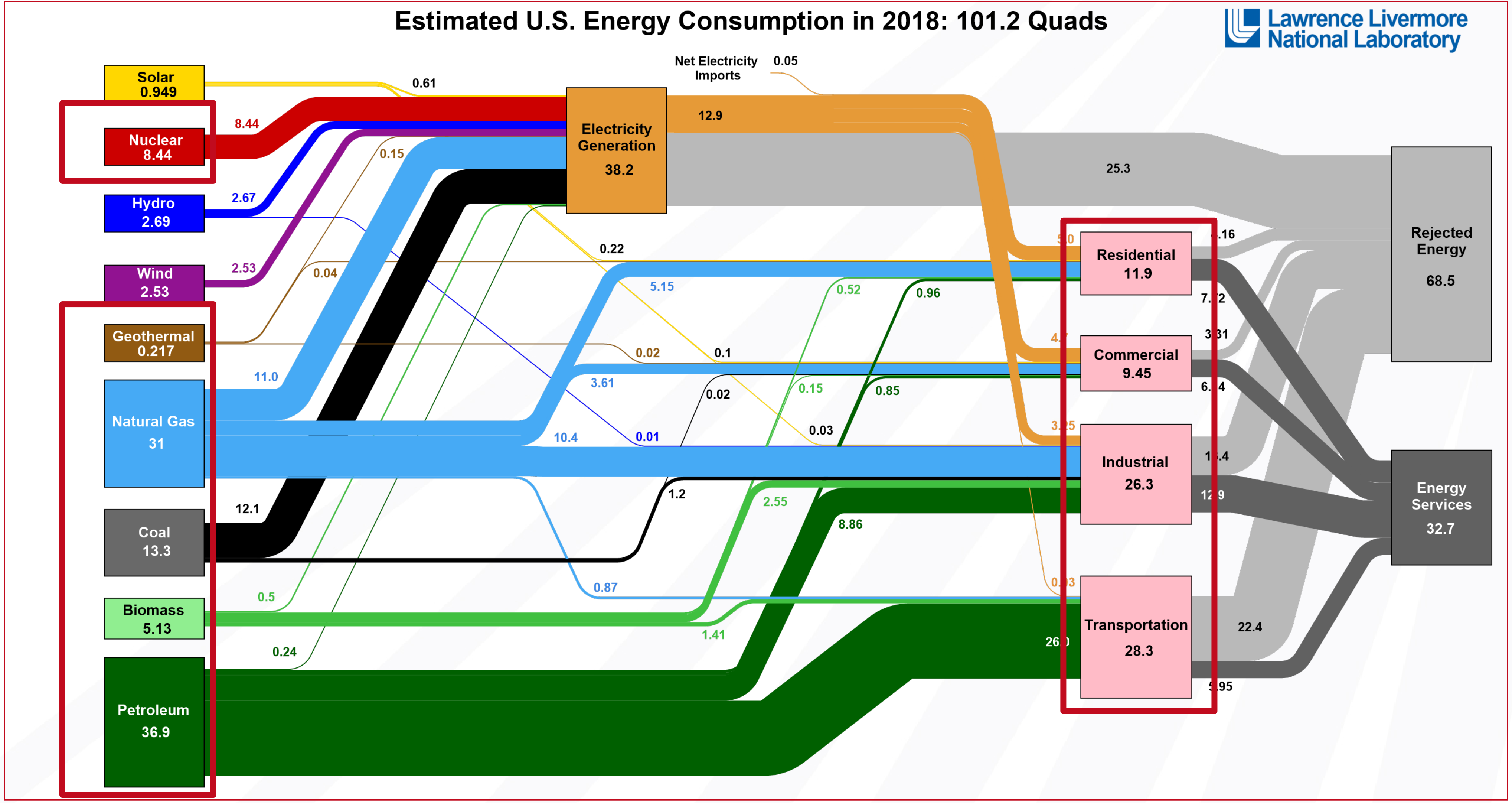
Renewable Power
Concentrating Solar

Advantages of the sCO_2 Brayton Cycle:

- Higher Efficiency (50% at ~720 C)
- Compact Components
- Smaller Turbine Footprint (by a factor > 10)
- Reduced Power Block Costs
- Amenable to Dry Cooling
- **Scalability (< 100 MW) with high efficiency**
- Operational Simplicity



Solar Thermal can Integrate with the Existing Energy System

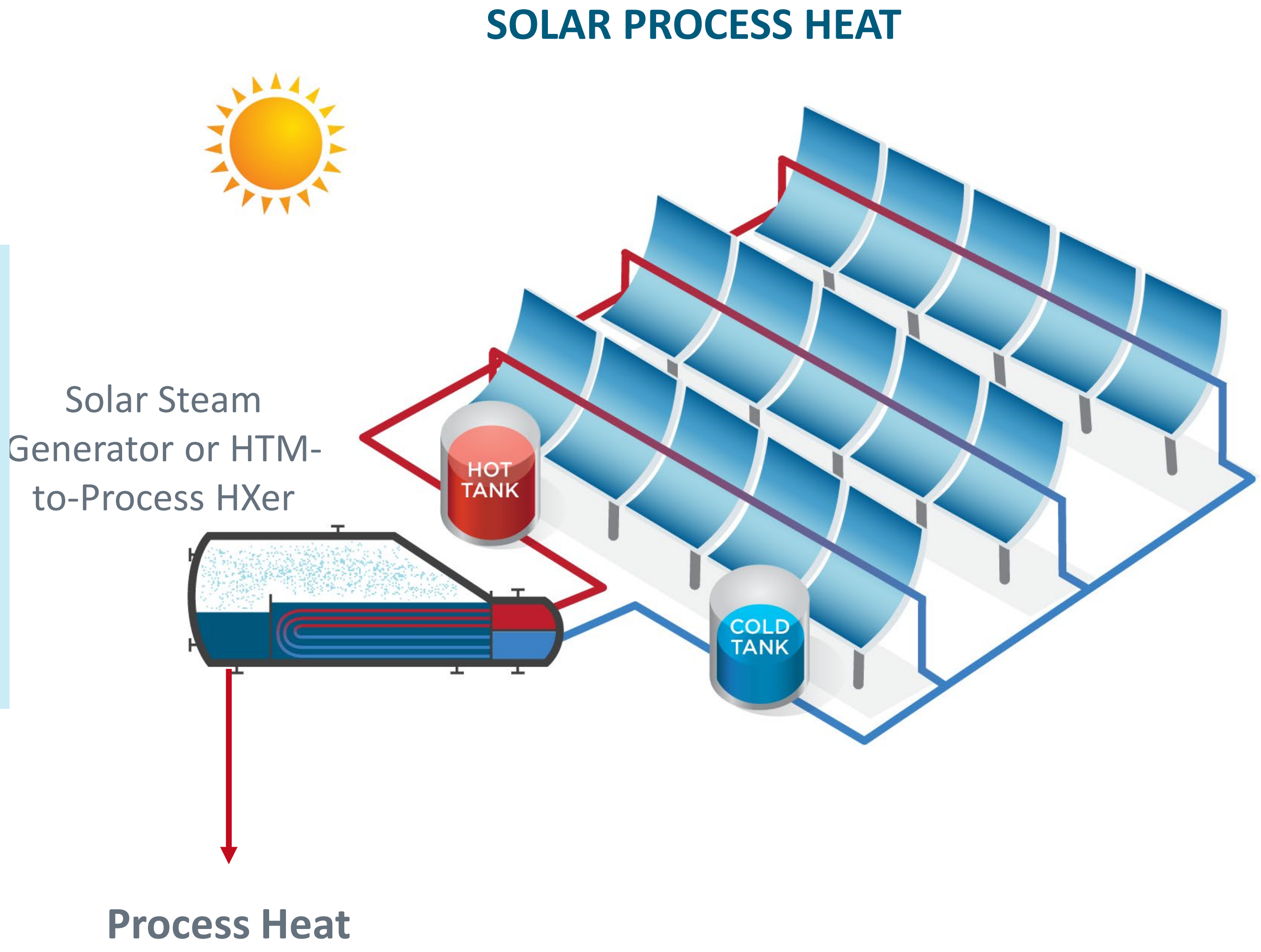


Estimated U.S. Energy Consumption in 2018: 101.2 Quads

Solar Thermal Industrial Process Heat

Thermally-Driven Industrial Processes:

- Desalination
- Enhanced Oil Recovery
- Agriculture and Food Processing
- Fuel and Chemicals Production
- Mining and Metals Processing



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- Autonomous, Integrated Heliostat Field & Components – **October 20th, 2020**
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*Full details and registration links will be posted here:

https://bit.ly/CSP-workshops

Problem Statement and Workshop Goals

Problem Statement

- ☐ Concentrated Solar Thermal applications are limited by the conditions (temperatures and solar flux) and control of converting concentrated light to thermal energy.
  - Gen3 CSP (for a 700°C sCO_2 Power Cycle)
  - Other Novel Electricity Generation embodiments
  - Long Duration Thermochemical Energy Storage
  - Solar Fuels
  - High Temperature Process Heat
  - Commodity Production

Workshop Goal

- ☐ Enable CSP stakeholders to engage with SETO and CSP Receiver experts in an informal panel format to share insights and lessons learned for developing and de-risking new receivers for new systems.
  - All statements made by panelists and participants are personal reflections, based on their experiences.

- ☐ Consider framework for advancing receiver innovations from idea to commercial adoption.

Generic Metrics Historically Used by SETO

Cost: $\$150/\text{kW}_{th}$

- Receiver Panel
- Auxiliary Components
- Piping (riser, downcomer)
- Cold Pump, Circulator, *etc*.
- Interconnects

Efficiency: 90% Optical to Thermal

- Incident Flux on Target / Thermal Energy Delivered to Storage
- Receiver Optical Properties
- Convection (wind)
- Consider Pressure and Parasitic Losses
- Conduction not recuperated

Lifetime: 30 Years

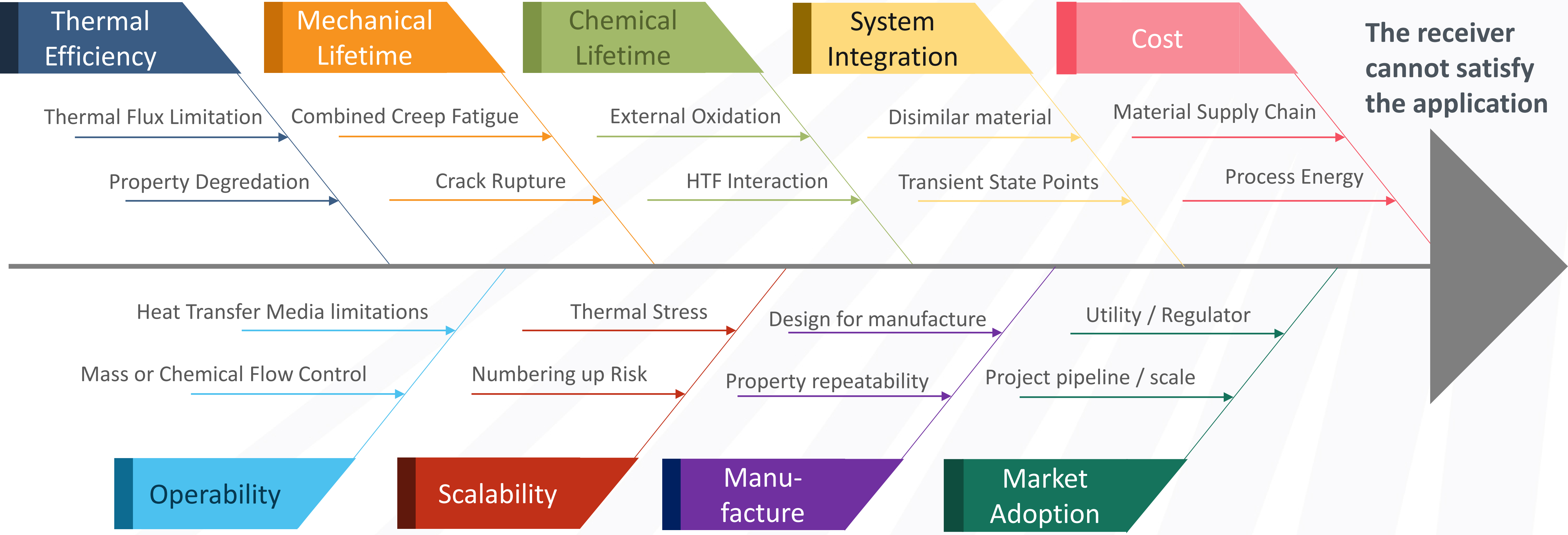
- Consistent with Financial Models informing SETO's Cost and Performance Targets
- Part Replacement accounting for additional O&M is a viable strategy

Application Specific Targets

- Gen3 CSP: Outlet Temperature > 720 °C
- Compatible with Dispatchable Thermal Energy Storage

Factors preventing innovative receivers

Ishikawa diagram approach



Thermal Efficiency
- Thermal Flux Limitation
- Property Degredation

Mechanical Lifetime
- Combined Creep Fatigue
- Crack Rupture

Chemical Lifetime
- External Oxidation
- HTF Interaction

System Integration
- Disimilar material
- Transient State Points

Cost
- Material Supply Chain
- Process Energy

Operability
- Heat Transfer Media limitations
- Mass or Chemical Flow Control

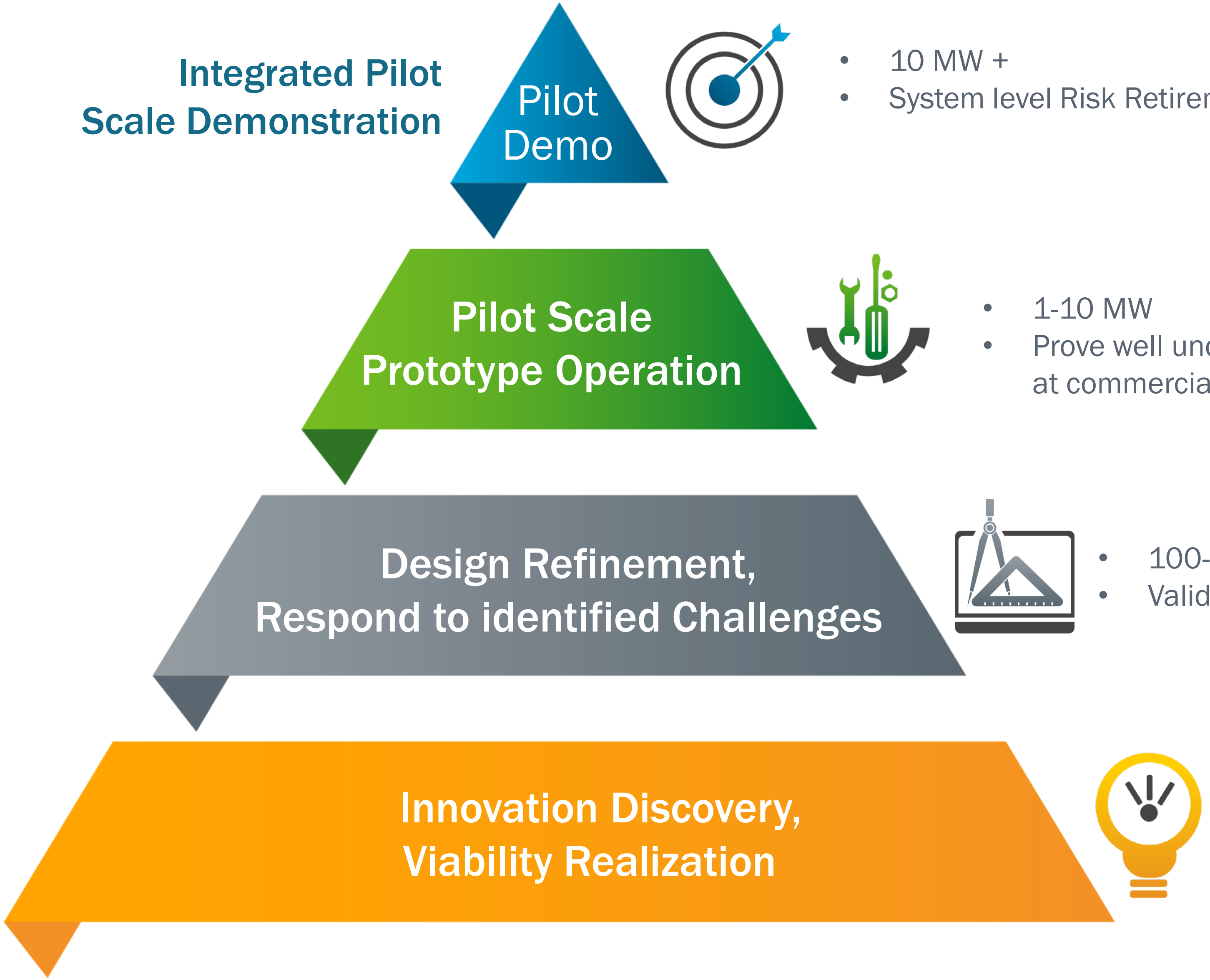
Scalability
- Thermal Stress
- Numbering up Risk

Manu-facture
- Design for manufacture
- Property repeatability

Market Adoption
- Utility / Regulator
- Project pipeline / scale

The receiver cannot satisfy the application

Thinking through Risk within Tiers of Technology Maturity



Integrated Pilot Scale Demonstration

Pilot Demo

- 10 MW +
- System level Risk Retirement

Pilot Scale Prototype Operation

- 1-10 MW
- Prove well understood models at commercial relevant scale

Design Refinement, Respond to identified Challenges

- 100-1,000 kW
- Validation and Isolated Risk Retirement

Innovation Discovery, Viability Realization

- 10-100 kW
- Conclusion Driven Research

Overlooked Target Audience

Who uses the knowledge from the campaign?

How does the audience impact development efforts?

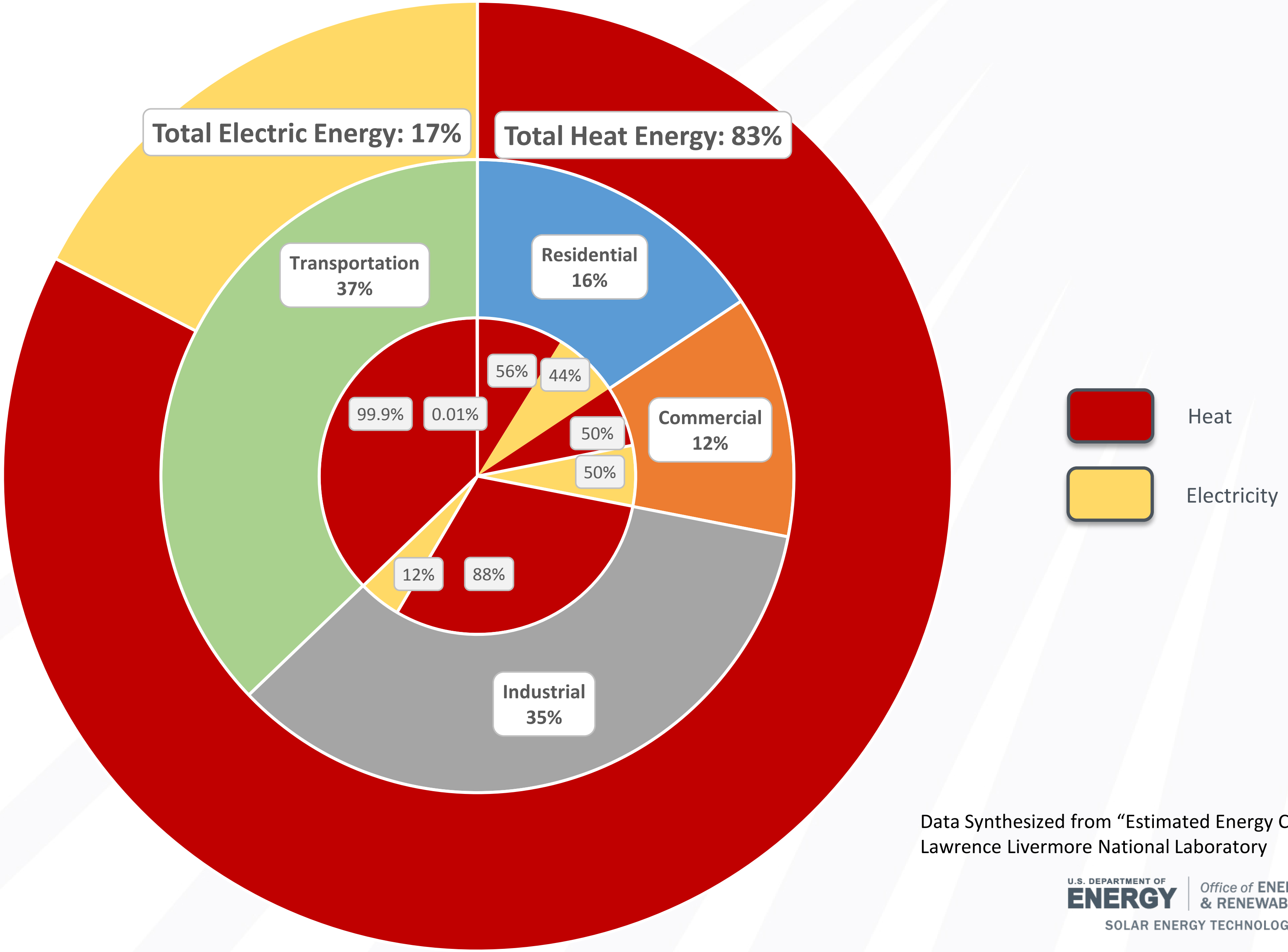
Target Audience:

- Research Peers
- Materials Manufacturers
- System Integrators
- Component Producers
- Commercial Project Developers
- Chemical or Commodity Producers
- Financers
- Utilities

Type of outputs

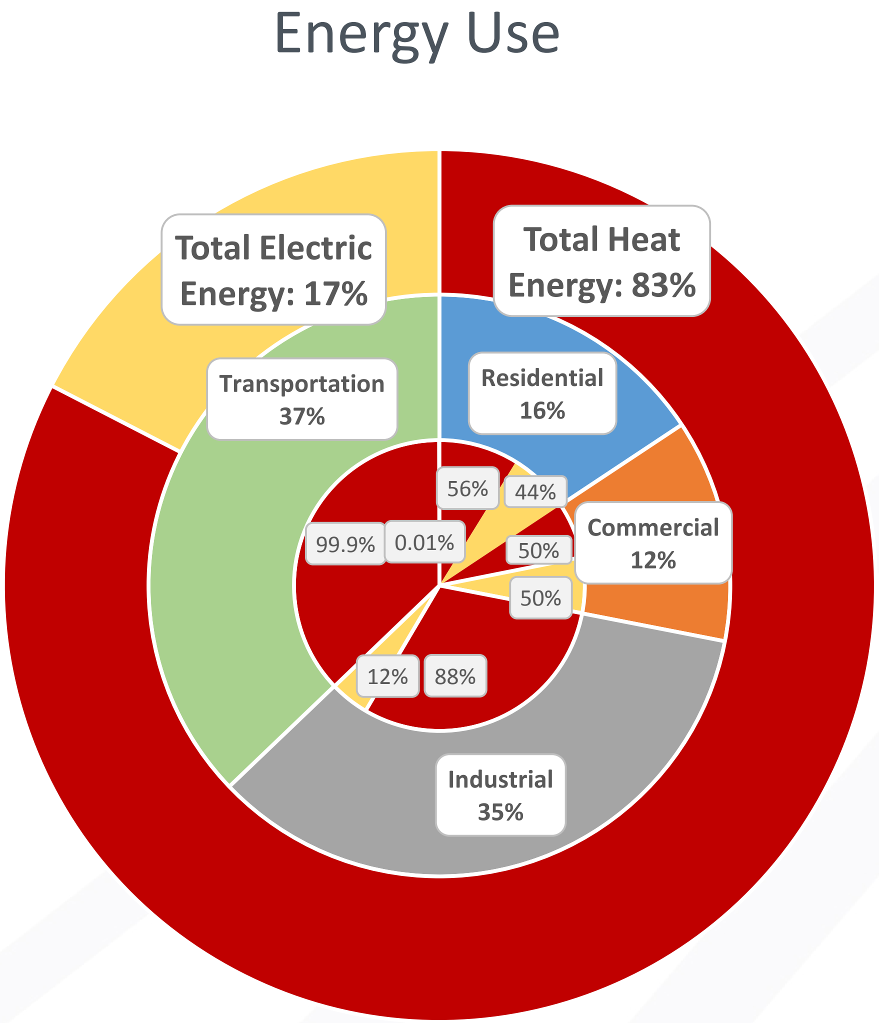
- Data Sets
- Manuscripts
- Sharable Code
- Off Design Performance
- Design Drawing
- Risk Assessment Formalism
- Market Analysis

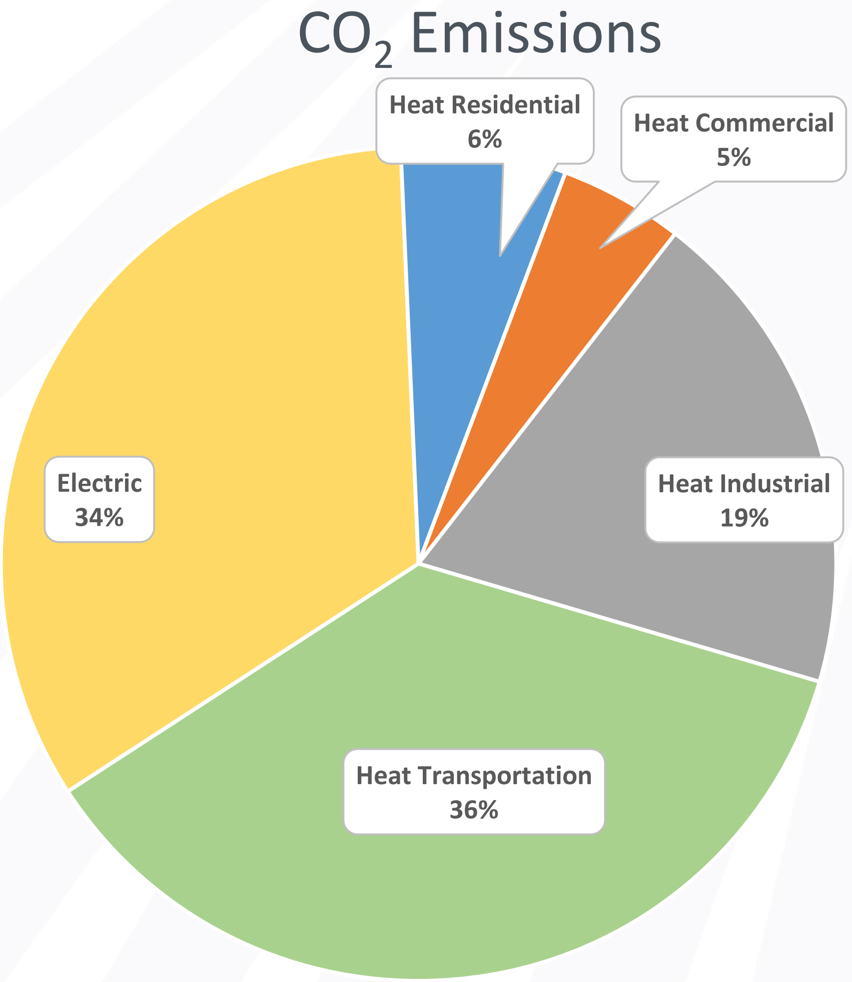
U.S. Energy use by Sector



Data Synthesized from “Estimated Energy Consumption in 2019”
Lawrence Livermore National Laboratory

U.S. Carbon Dioxide Emissions by Sector





Data Synthesized from “US Carbon Dioxide Emissions in 2018”
Lawrence Livermore National Laboratory

Innovation is Critical!

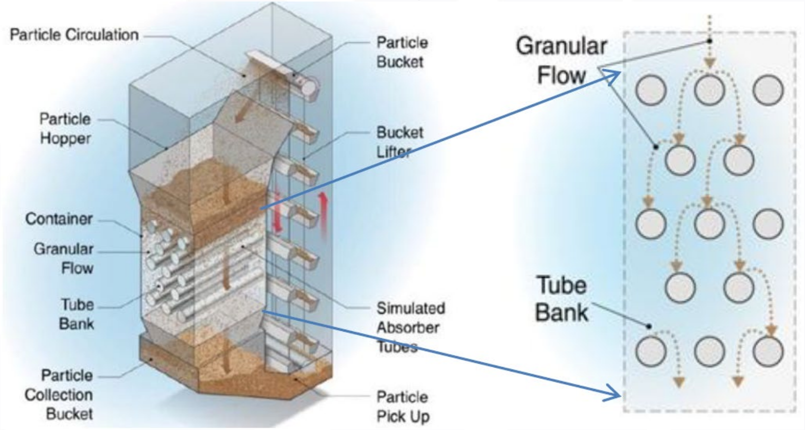
Ceramic Tubular Products

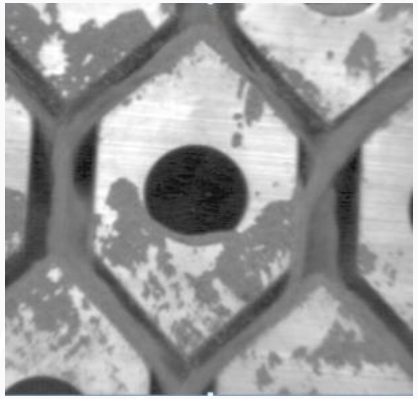
Silicon Carbide Composite

Jeff Halfinger: ctp-usa.com

National Renewable Energy Laboratory

“Black Body” Enclosed Particle Receiver

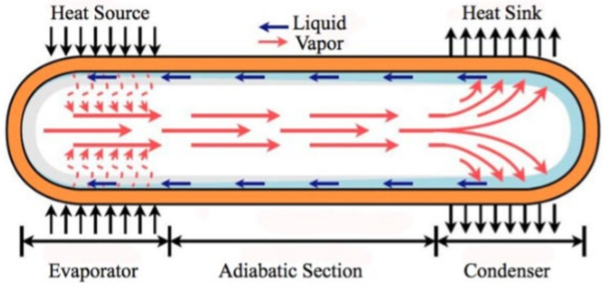




Zhiwen Ma

Los Alamos National Laboratory

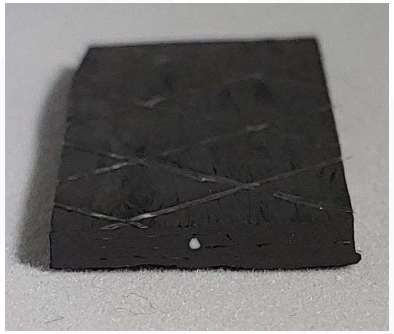
Counter Gravity Heat Pipe Receiver

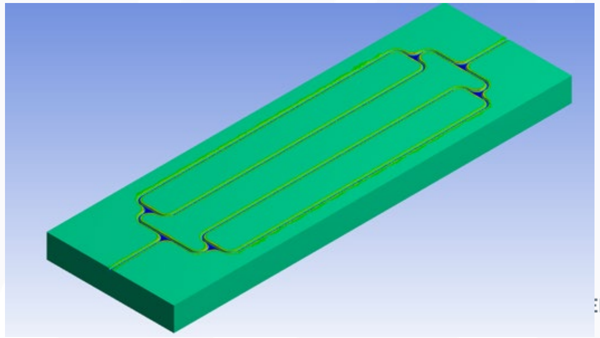


Steve Obrey

University of Tulsa

Microvascular Carbon Composite Receiver



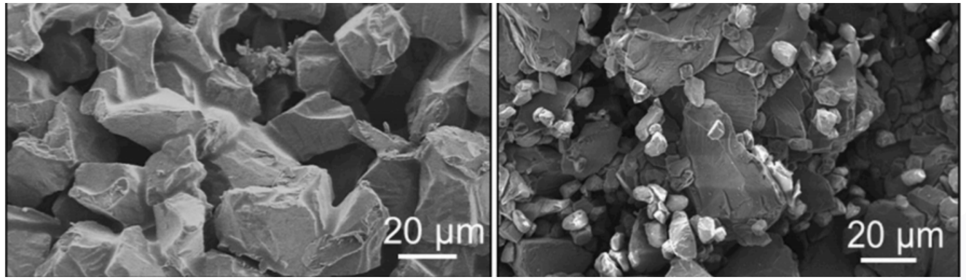


Michael Keller

Innovation is Critical

Argonne National Laboratory

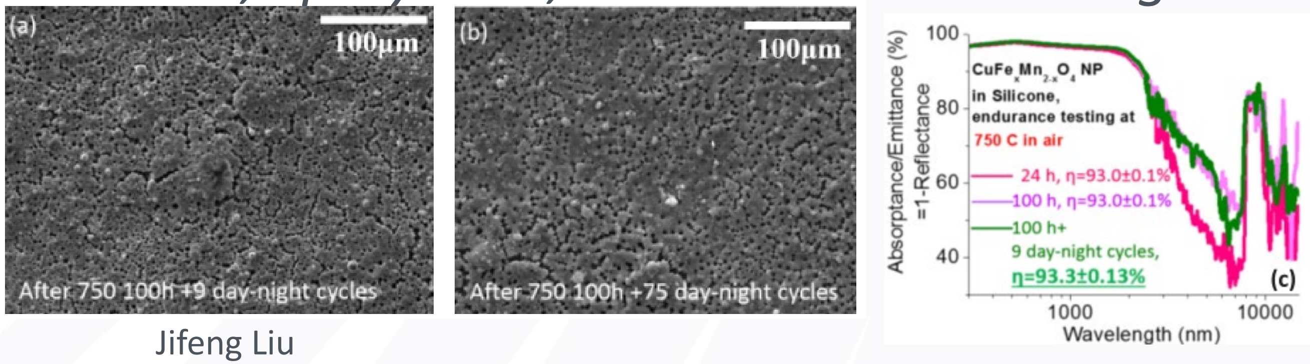
Binder Jet Add. Manf. with MAX Phase Mats.



Dileep Singh

Dartmouth College

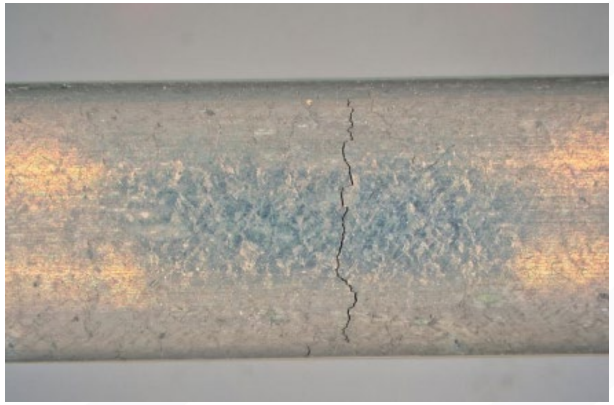
Stable, Spray-able, Solar Selective Coatings

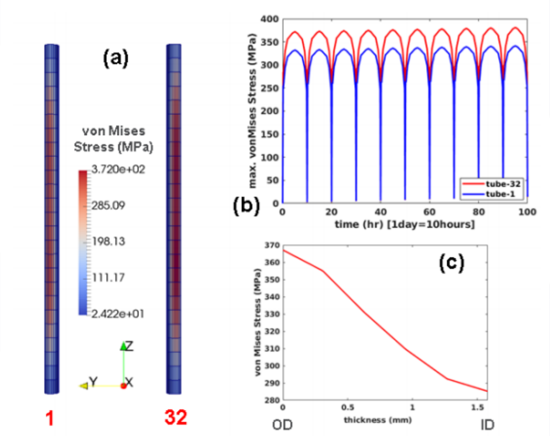


Jifeng Liu

Idaho National Laboratory

Creep-Fatigue Behavior in Nickel Alloys

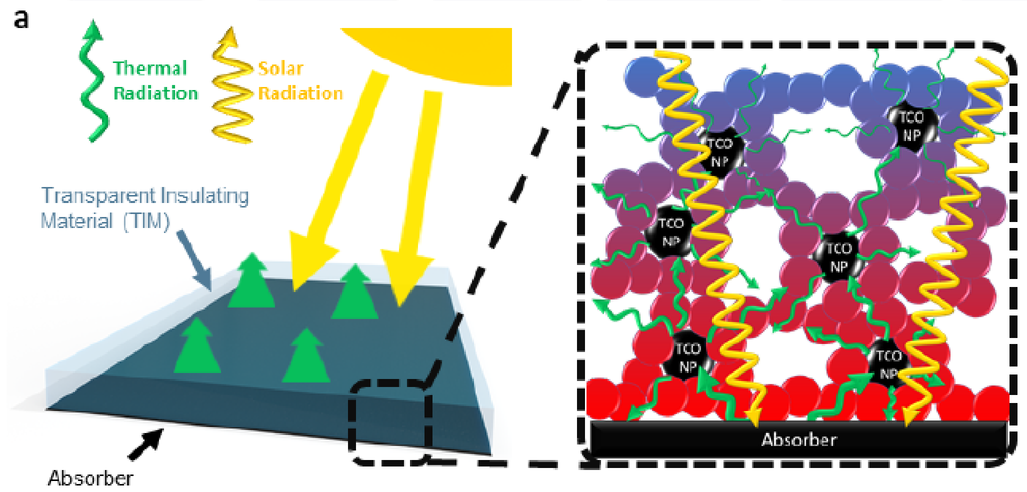




Mike McMurtrey

University of Michigan

Spectrally Selective Aerogels



Andrej Lenert

Agenda

Time	Session
1:00PM– 1:30PM	**Introduction and Workshop Overview** Avi Shultz, *DOE Program Manager, Concentrating Solar Power* Matthew Bauer, *DOE Technology Manager, Concentrating Solar Power*
1:30PM– 3:00PM	**Panel – First of a Kind Receiver Development for Gen3 CSP** Cliff Ho, *Sandia National Laboratories* Shaun Sullivan, *Brayton Energy* Craig Turchi, *National Renewable Energy Laboratory*
3:00PM– 4:30PM	**Panel – Impactful R&D for Technology Adoption** Brian Fronk, *Oregon State University* Michael Wagner, *University of Wisconsin* Mark Messner, *Argonne National Laboratory* David Wait, *Nooter/Eriksen*
4:30 PM	**Closing Remarks** Matthew Bauer, *Department of Energy*


Gen3CSP
Bringing together *the* **people** *and the* **pieces** *for an*
INTEGRATED CSP SYSTEM

First of a Kind Receiver Development for Gen3 CSP

Cliff Ho SNL
2012: Particle Receiver / System
2015: Particle Mass Control
2018: Gen3 Particle Pilot Plant

Shaun Sullivan Brayton Energy
2012: Direct sCO_2 Receiver
2015: Metal Hydride Receiver/System
2018: Gen3 Gas System

Craig Turchi NREL
2012: sCO_2 Turbine Test
2015: CSP System Analysis
2018: Gen3 Liquid Pathway to SunShot

Panel 1 Themes (FOAK Gen3 Receivers)

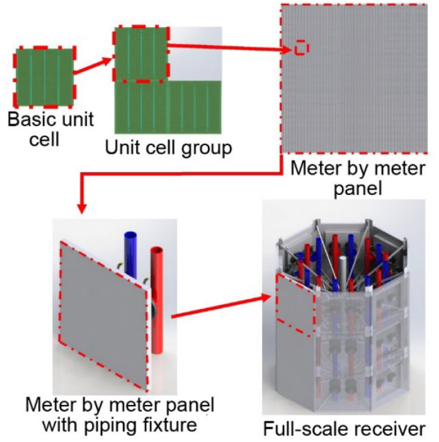
- When scaling innovations from lab-scale research to on-sun demonstration and to commercial scale deployments, what are the key risks that are often overlooked in the development process?
  - What overlooked technical metrics/objectives should be considered in both early and late stages of receiver R&D?
  - What accomplishments are needed to adequately de-risk a receiver for 10 MW demonstration and beyond?

- What innovations could impact, improve, or shift the paradigm for a Gen3 System's receiver?

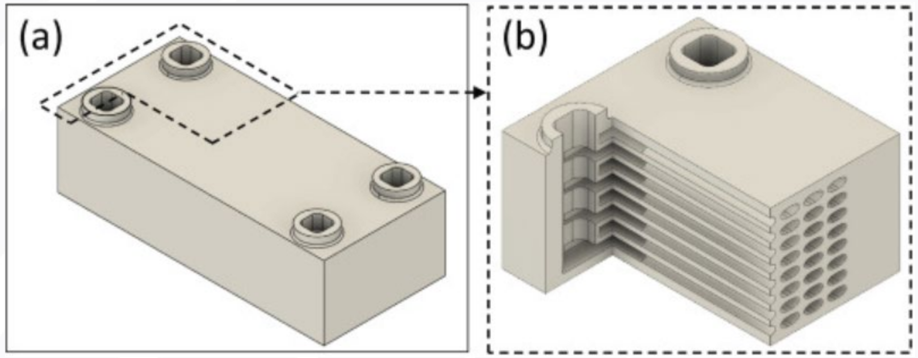
- How should a system integrator go about balancing constraints between the receiver and the remainder of the power plant?

Impactful R&D for Technology Adoption

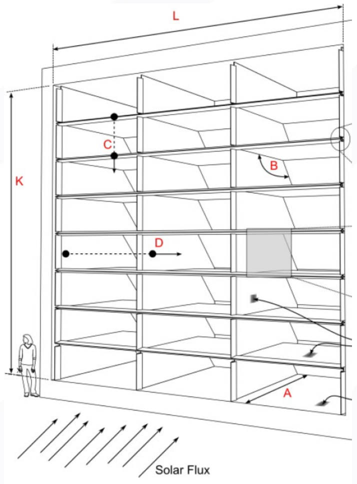
Brian Fronk Oregon State U.



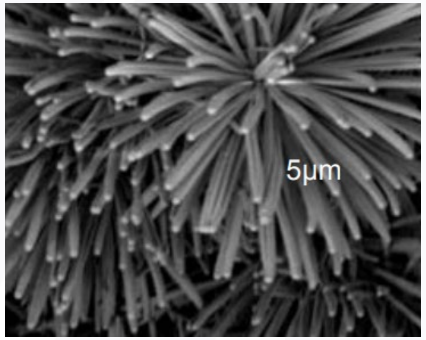
Mark Messner Argonne National Laboratory



Mike Wagner U. of Wisconsin



David Wait Nooter/Eriksen



Panel 2 Themes (Impactful Receiver R&D)

- When scaling innovations from lab-scale research to on-sun demonstration and to commercial scale deployments, what are the key risks that are often overlooked in the development process?

- How does one go about making an innovation bankable?
  - For a specified risk, how is an adequately de-risked handoff achieved?
  - What standards exist for proving and scaling up innovations?

- What risks exist physically interfacing a specified innovation with the remainder of the system? How are they overcome?

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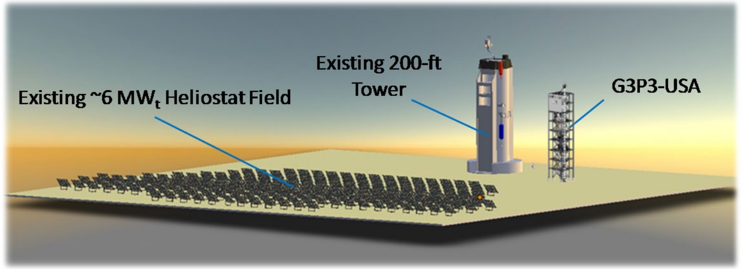
Gen3 Particle Pilot Plant (G3P3) Receiver Design and Testing



PRESENTED BY

Clifford K. Ho

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

Contributors:

SNL: Nathan Schroeder, Henk Laubscher, Lindsey Yue, Brantley Mills, Reid Shaeffer, Joshua Christian, and Kevin J. Albrecht

Others: Georgia Tech, King Saud U., DLR, ANU, CSIRO, U. Adelaide, CNRS-PROMES, CARBO Ceramics

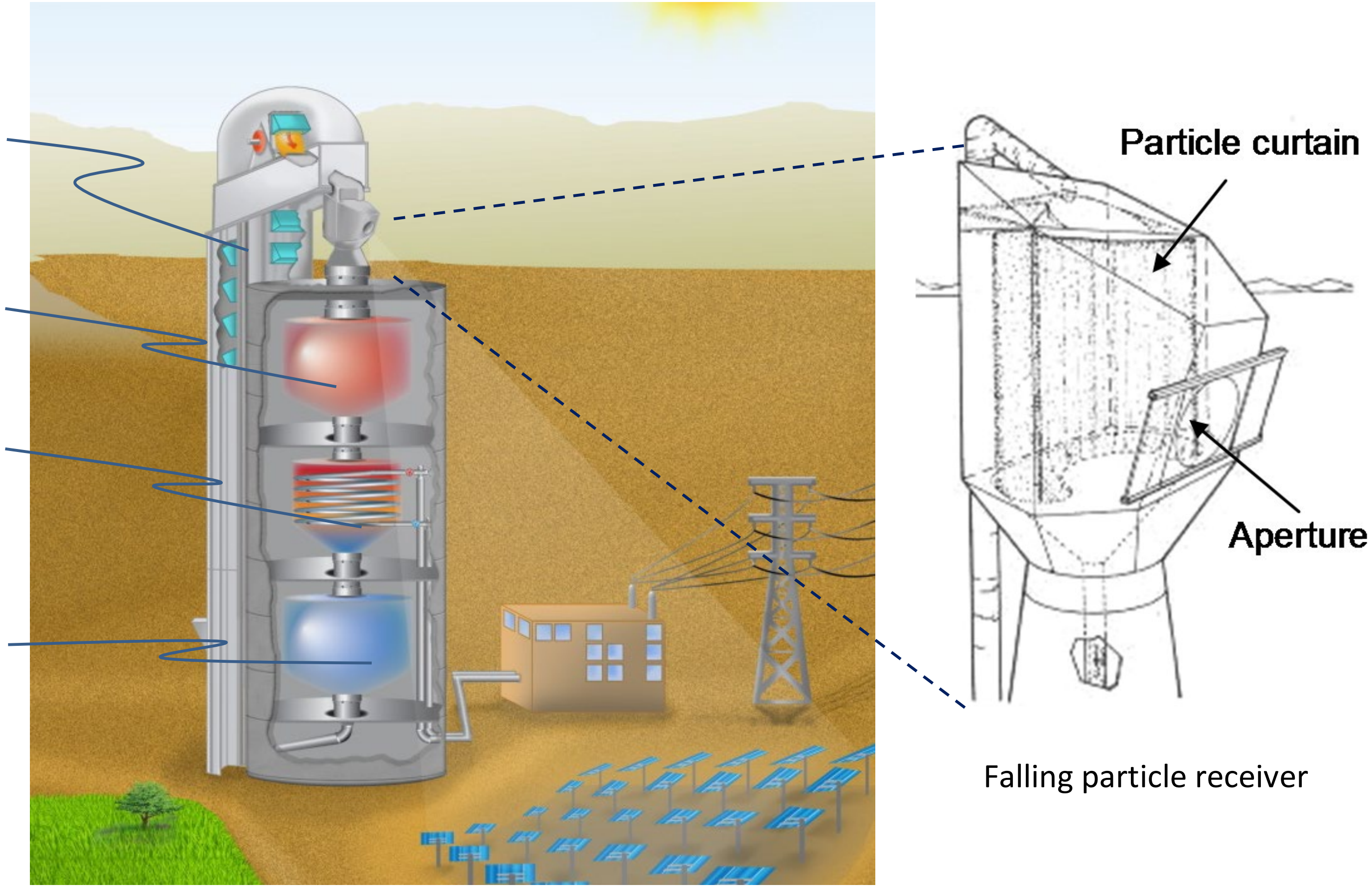
SAND2020-11936 PE

Overview

- Introduction and Objectives
- Receiver Design
- On-Sun Testing
- Lessons Learned

Background and Introduction

High-Temperature Particle-Based CSP



Particle elevator

Particle hot storage tank

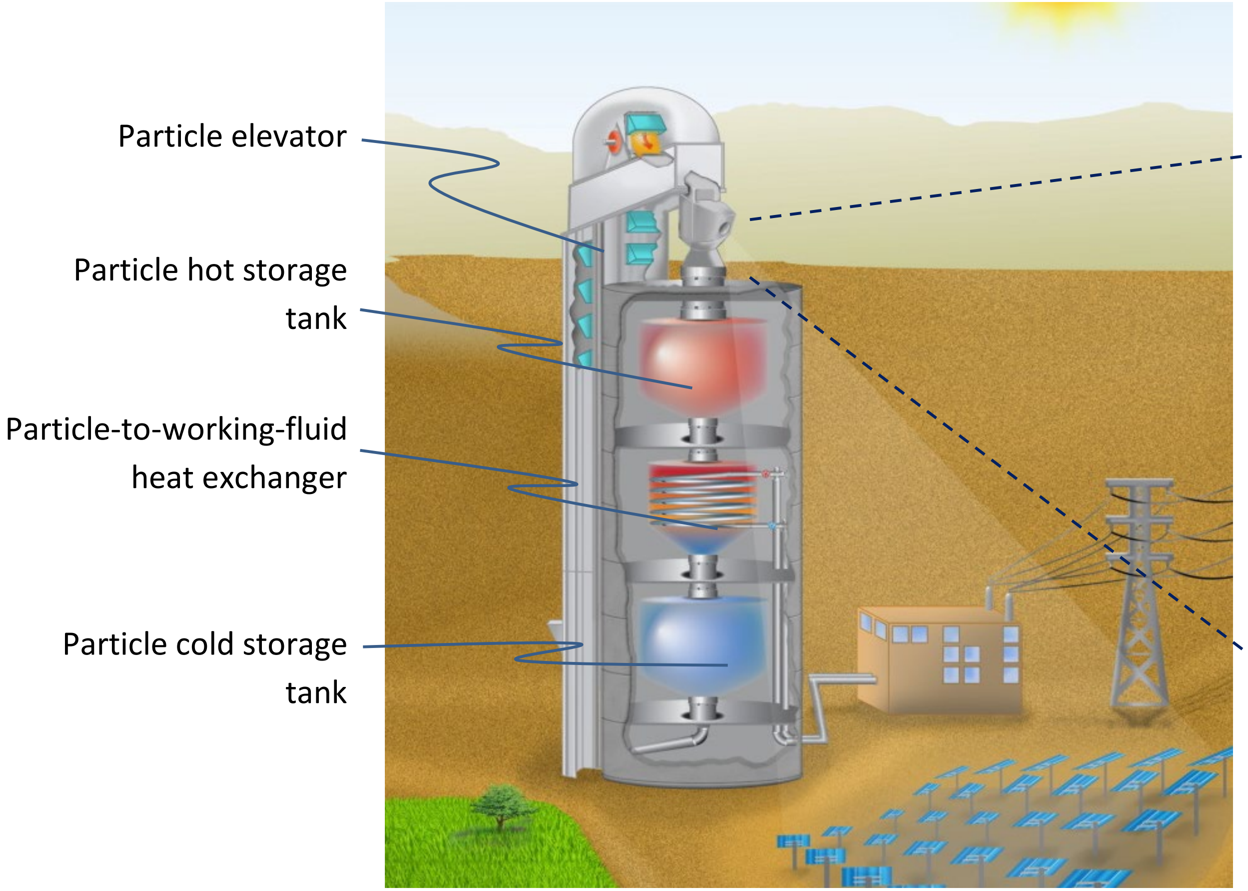
Particle-to-working-fluid heat exchanger

Particle cold storage tank

Falling particle receiver

Background and Introduction

High-Temperature Particle-Based CSP



Particle elevator

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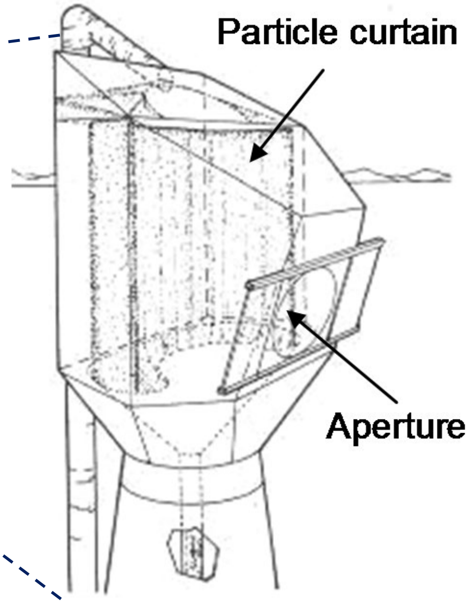
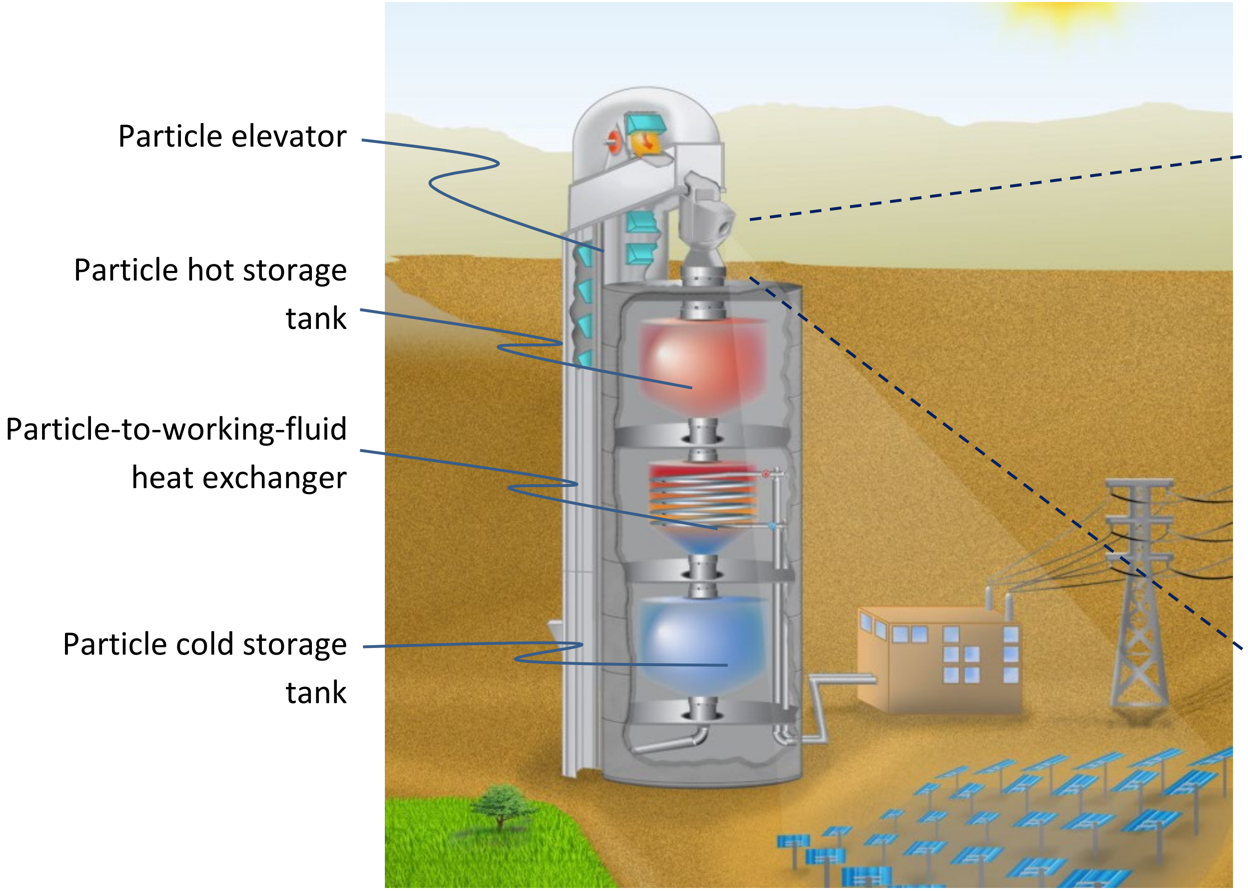


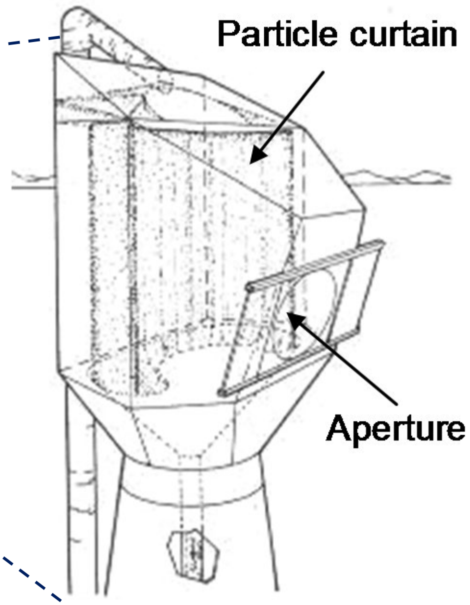
Falling particle receiver

National Solar Thermal Test Facility
Sandia National Laboratories

Background and Introduction

High-Temperature Particle-Based CSP



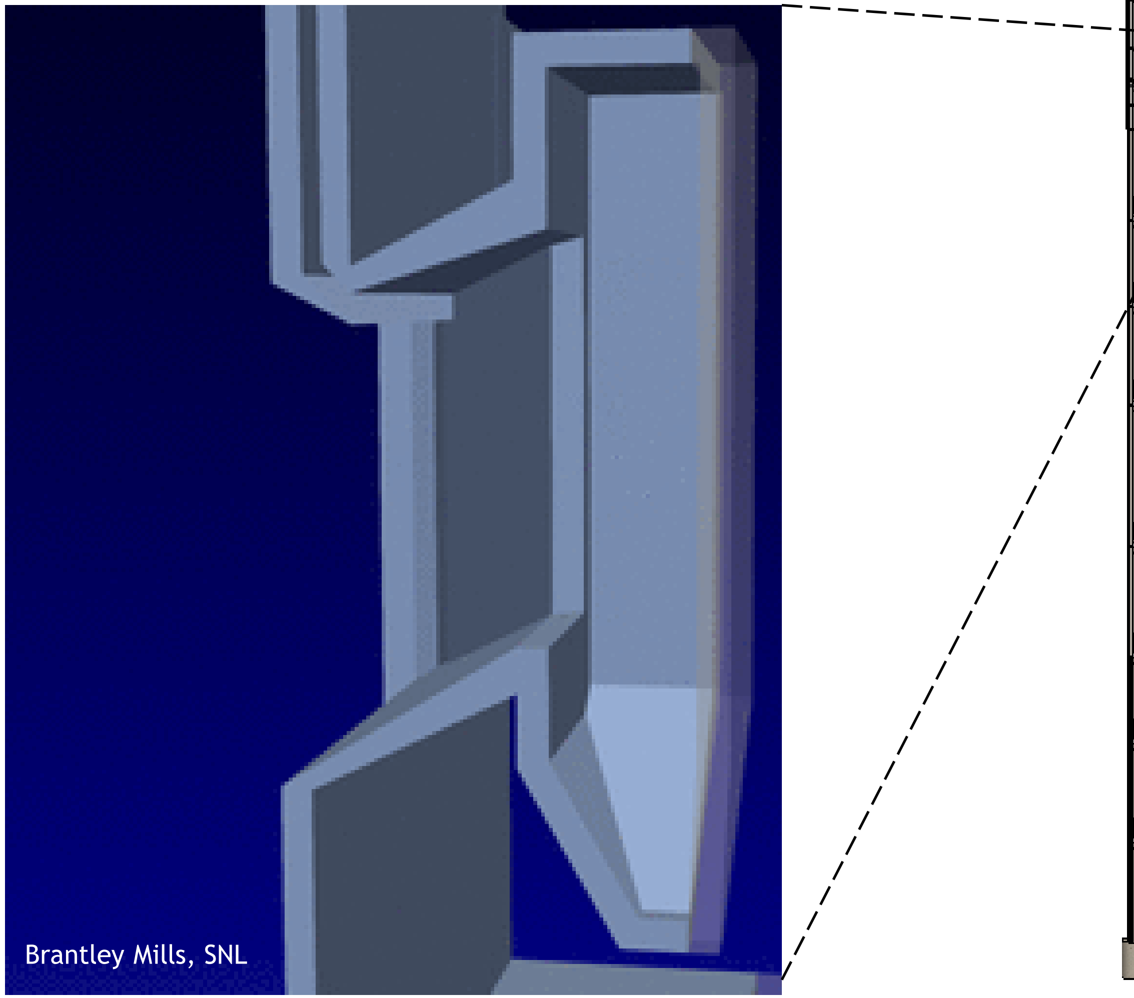


Falling particle receiver

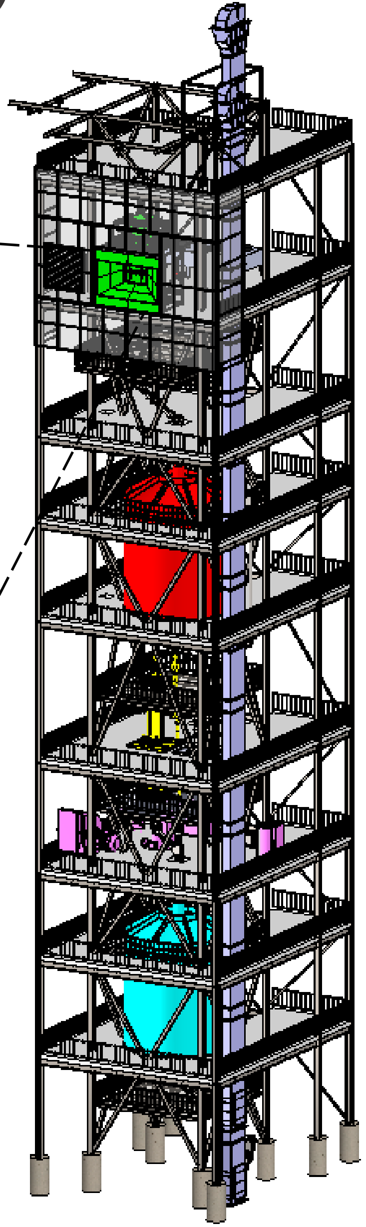
- Higher temperatures (>1000 ˚C) than molten nitrate salts
- Direct heating of particles vs. indirect heating of tubes
- No freezing or decomposition
  - Avoids costly heat tracing
- Direct storage of hot particles

Gen3 Particle Pilot Plant (G3P3)

Next-Generation High-Temperature Falling Particle Receiver



Brantley Mills, SNL



K. Albrecht, SNL

Gen 3 Particle Pilot Plant

- ~1 – 2 MW_t receiver
- 6 MWh_t storage
- 1 MW_t particle-to-sCO_2 heat exchanger
- ~300 – 400 micron ceramic particles (CARBO HSP 40/70)

Objectives

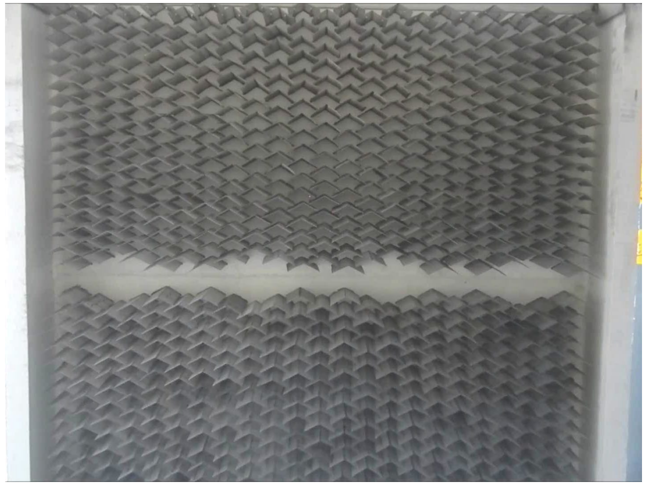
- Present evolution of receiver design for G3P3
- Describe on-sun testing to evaluate performance of new design features and obtain operational experience
- Identify system interfaces, design challenges, and lessons learned

Overview

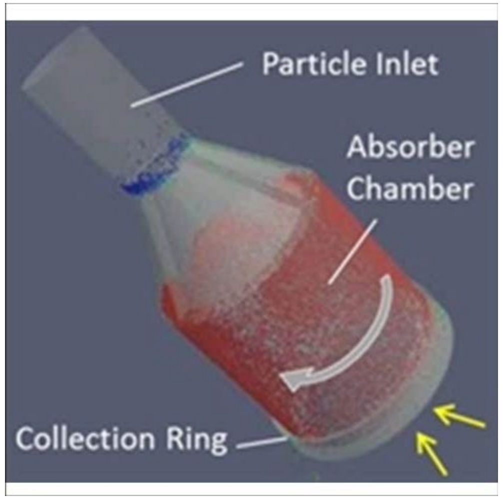
- Introduction and Objectives
- Receiver Design
- On-Sun Testing
- Lessons Learned

Alternative Particle Receiver Designs

Free-Falling (SNL)



Obstructed Flow
(Georgia Tech, King Saud U.)



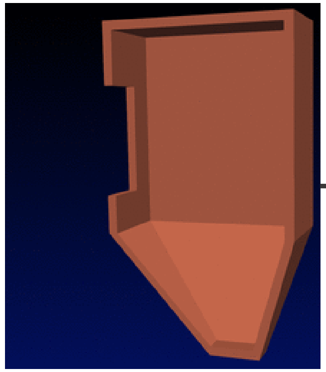
Centrifugal (DLR)

Fluidized Bed

G3P3-USA Receiver Design Evolution

2015 – 2018

NSTTF
1 MW_{th} FPR

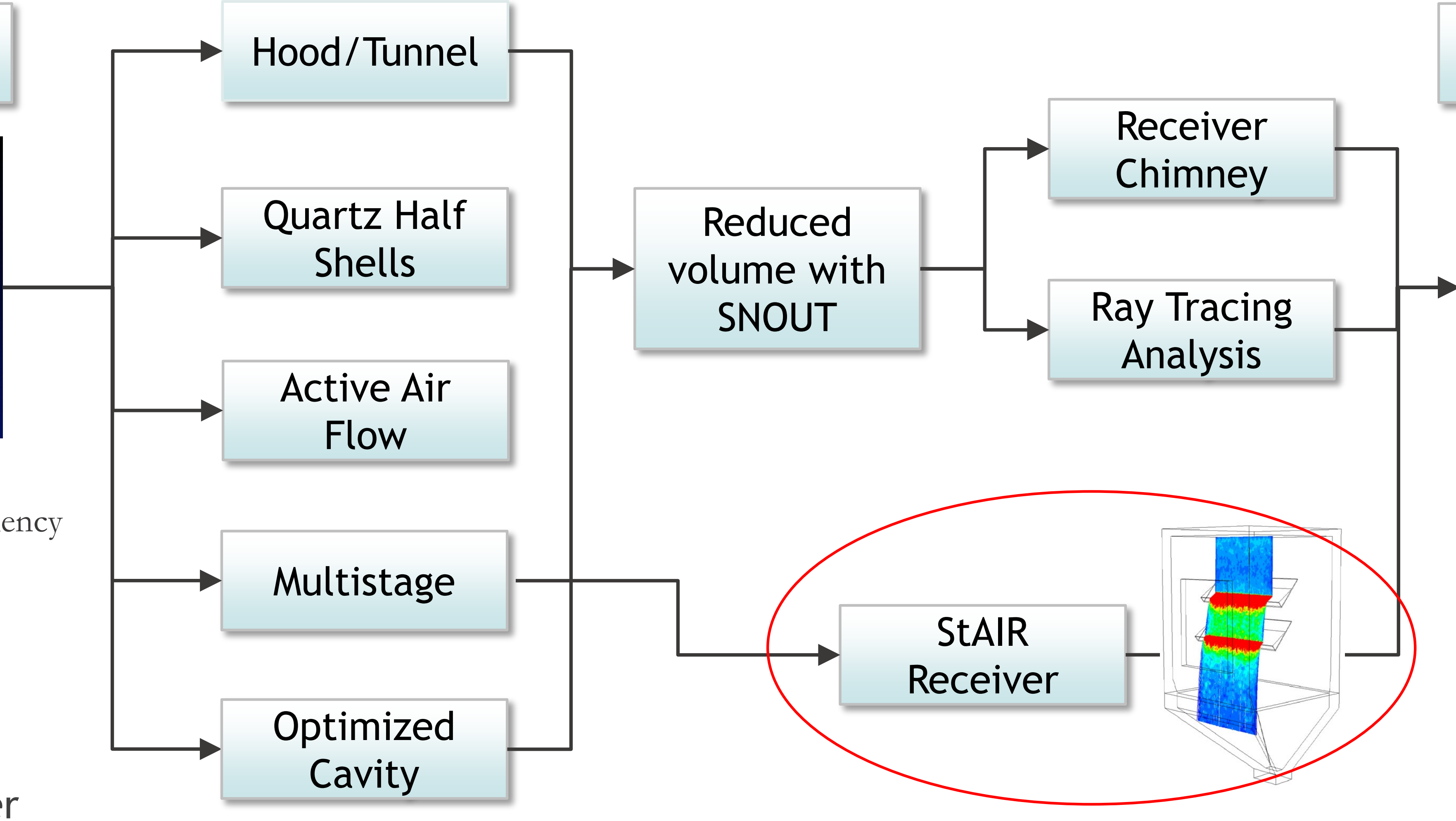


Design Challenges
- Low thermal efficiency
- Sensitivity to wind

FPR = Falling particle receiver

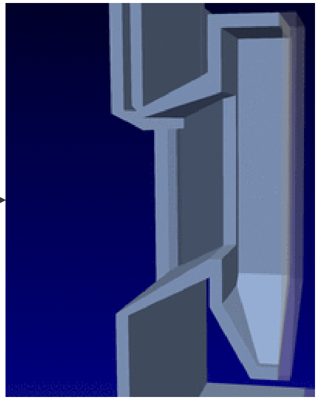
Feature evaluation

Design refinement



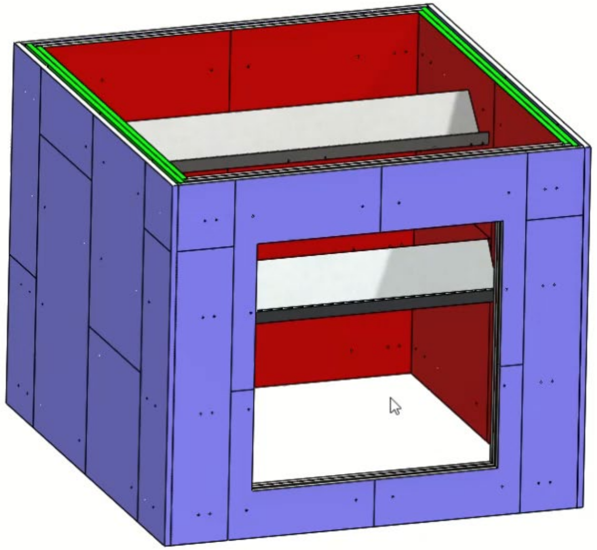
2020
Design evaluation

Optimized
G3P3 FPR

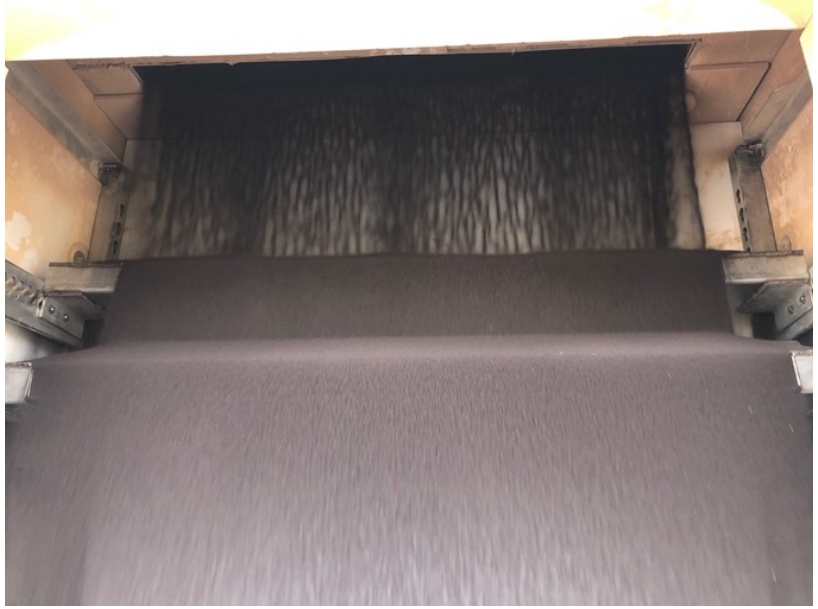


Pathway
- Wind Evaluation
- Ground Testing
- On-sun Testing
- Model Validation

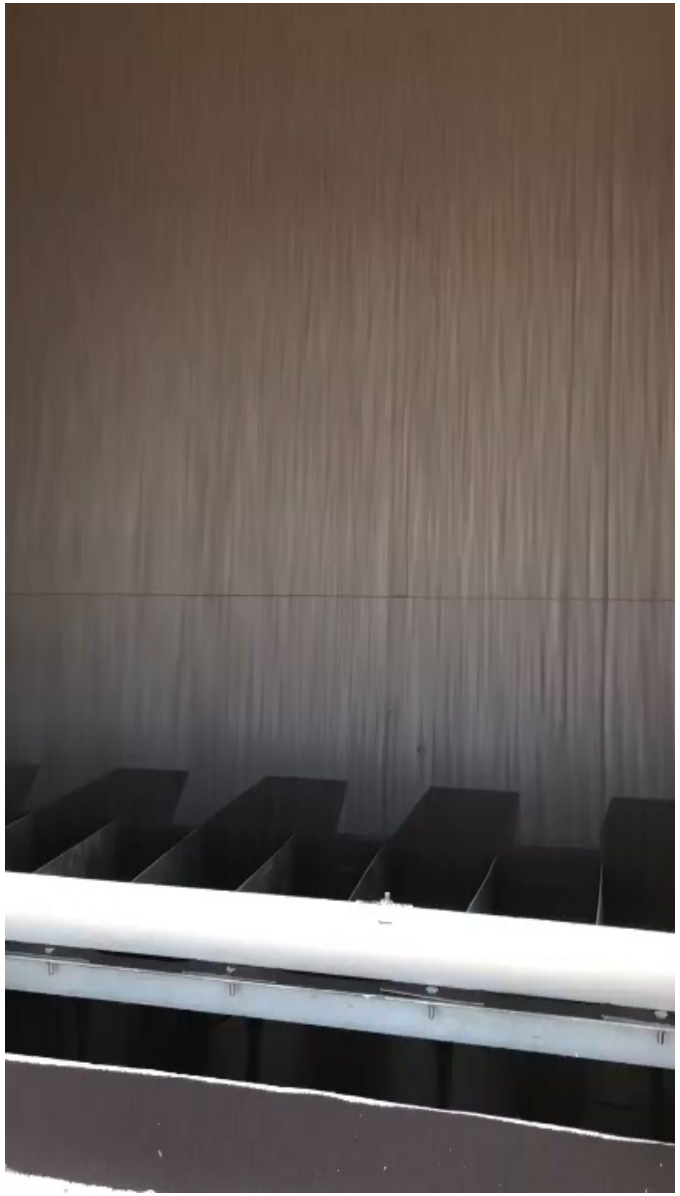
StAIR (Staggered Angle Iron Receiver) Testing



Drawing of “stairs” in receiver cavity

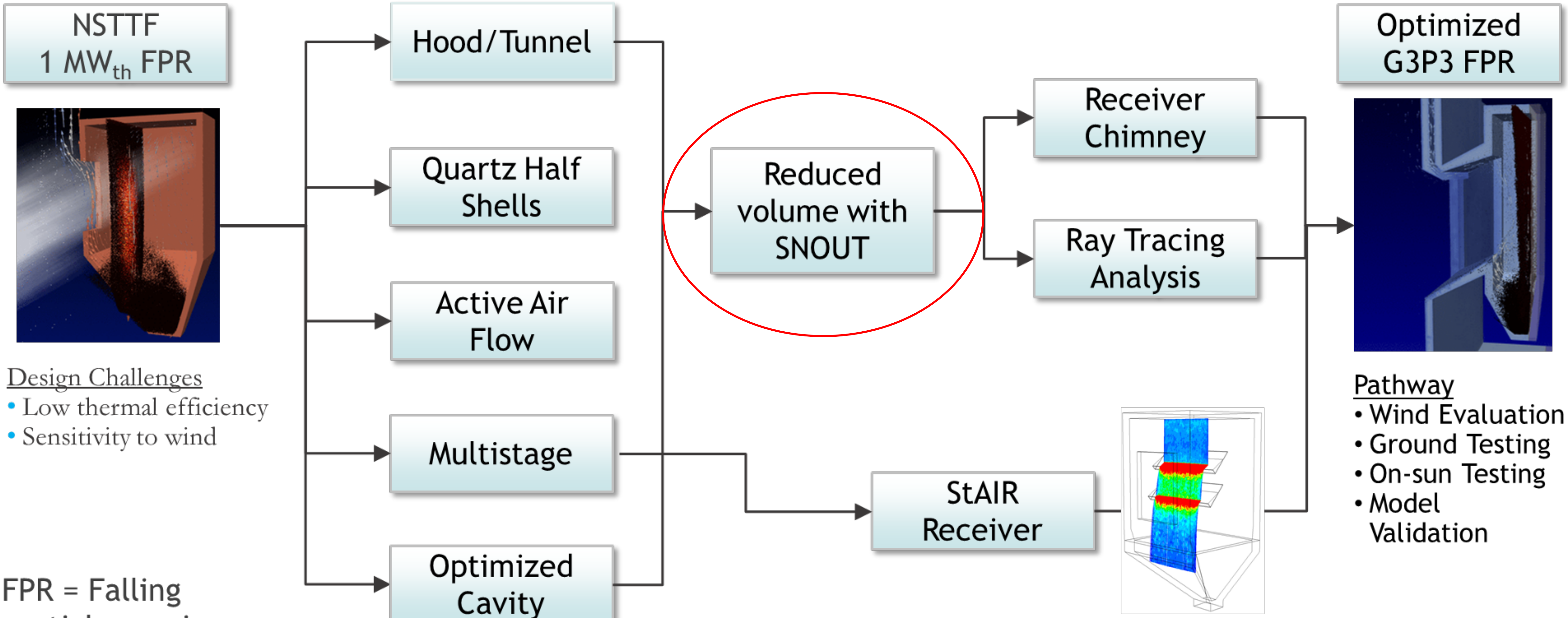


Particle flow over two-stair configuration (5 – 10 kg/s)



StAIRS create a more uniform and opaque particle curtain for increased solar absorptance

G3P3-USA Receiver Design Evolution



2015 - 2018

Feature evaluation

Design refinement

2020

Design evaluation

NSTTF
1 MW_{th} FPR

Design Challenges
- Low thermal efficiency
- Sensitivity to wind

Hood/Tunnel

Quartz Half Shells

Active Air Flow

Multistage

Optimized Cavity

Reduced volume with SNOUT

Receiver Chimney

Ray Tracing Analysis

StAIR Receiver

Optimized G3P3 FPR

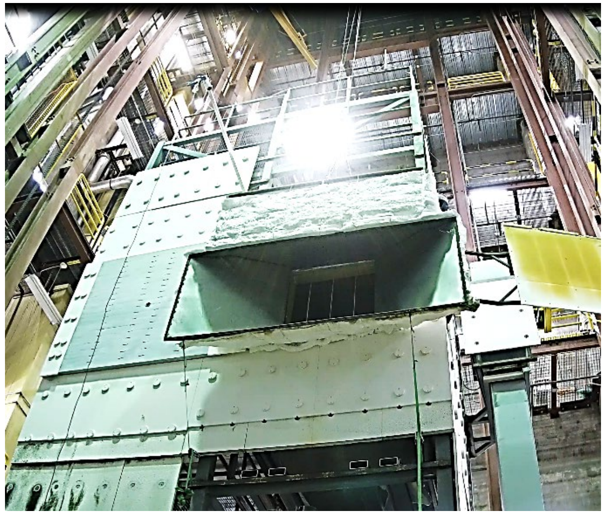
Pathway
- Wind Evaluation
- Ground Testing
- On-sun Testing
- Model Validation

FPR = Falling particle receiver

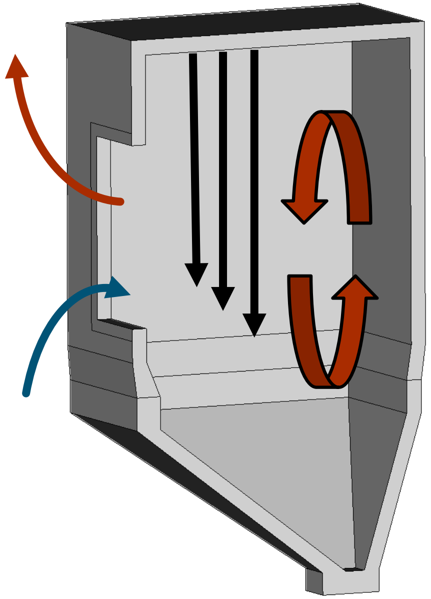
SNOUT and Reduced Volume Receiver

Baseline

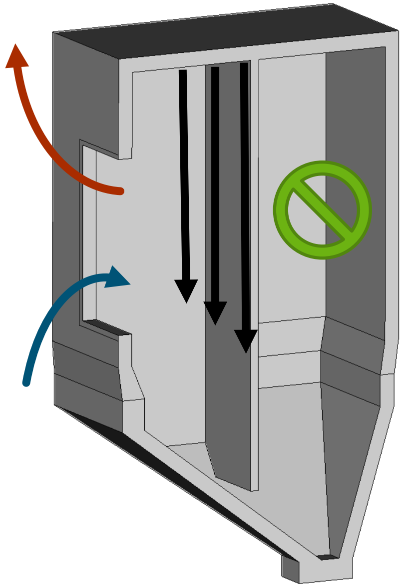
SNOUT

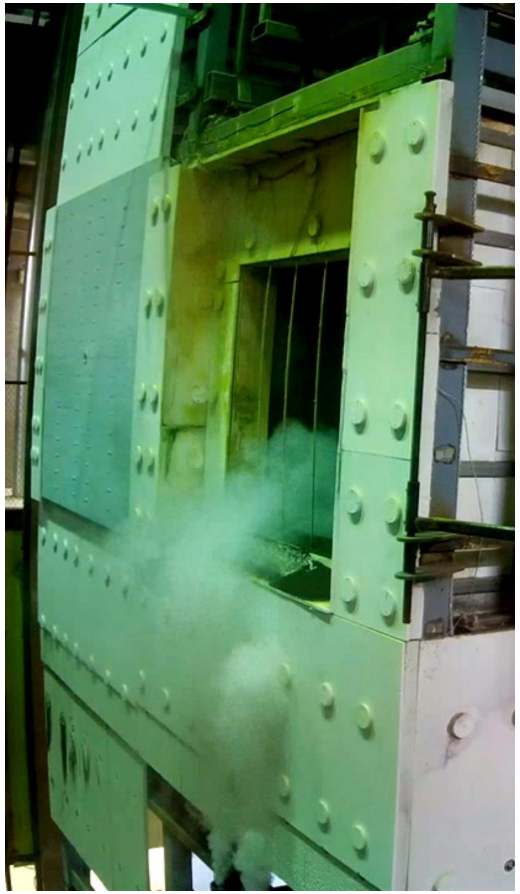


Baseline



Reduced volume receiver





Experiment

Simulation

SNOUT and reduced-volume reduced advective heat loss by ~20 – 25%

Overview

- Introduction and Objectives
- Receiver Design
- On-Sun Testing
- Lessons Learned

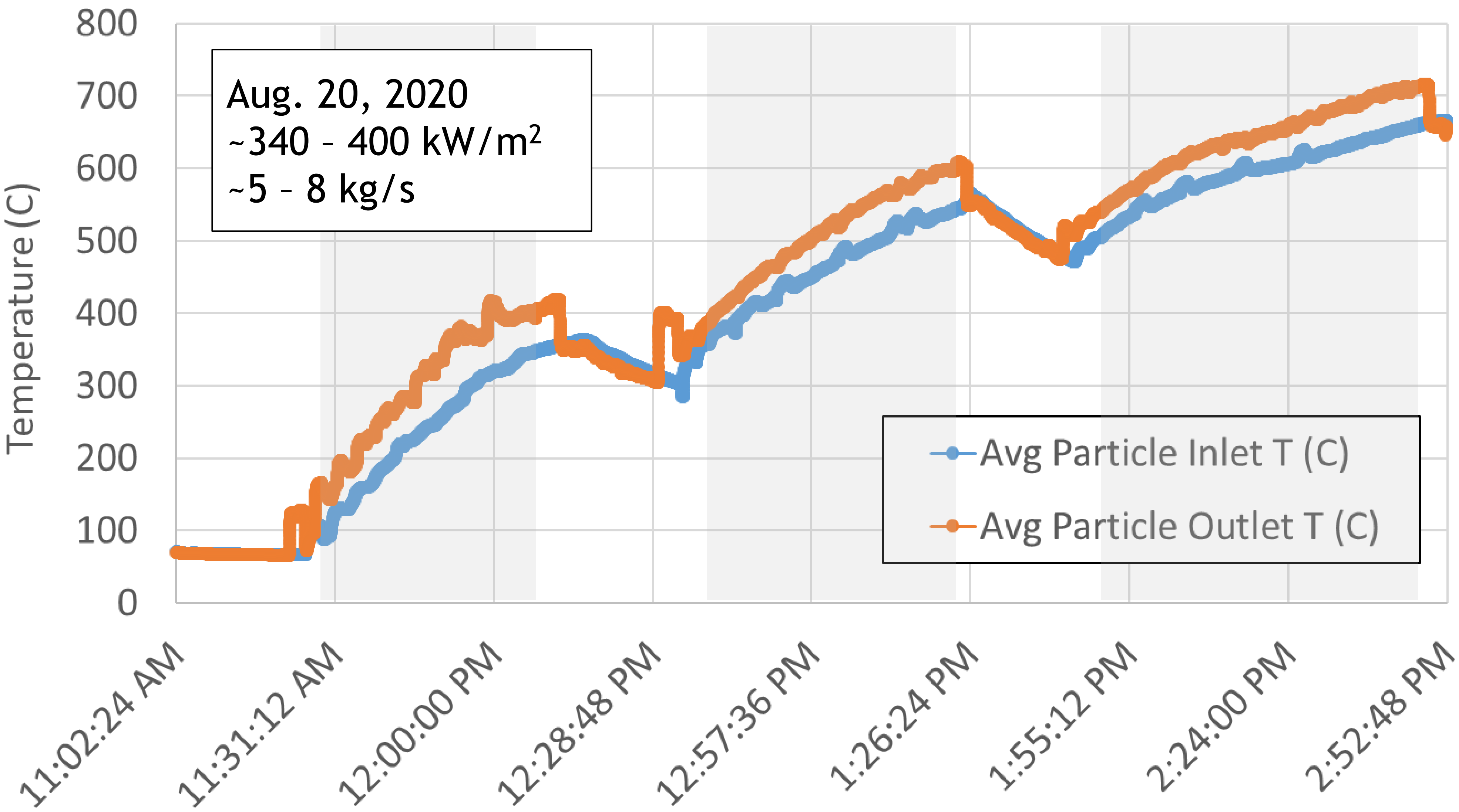
Control Room and On-Sun Testing

On-sun testing of particle receiver with StAIRs and reduced volume

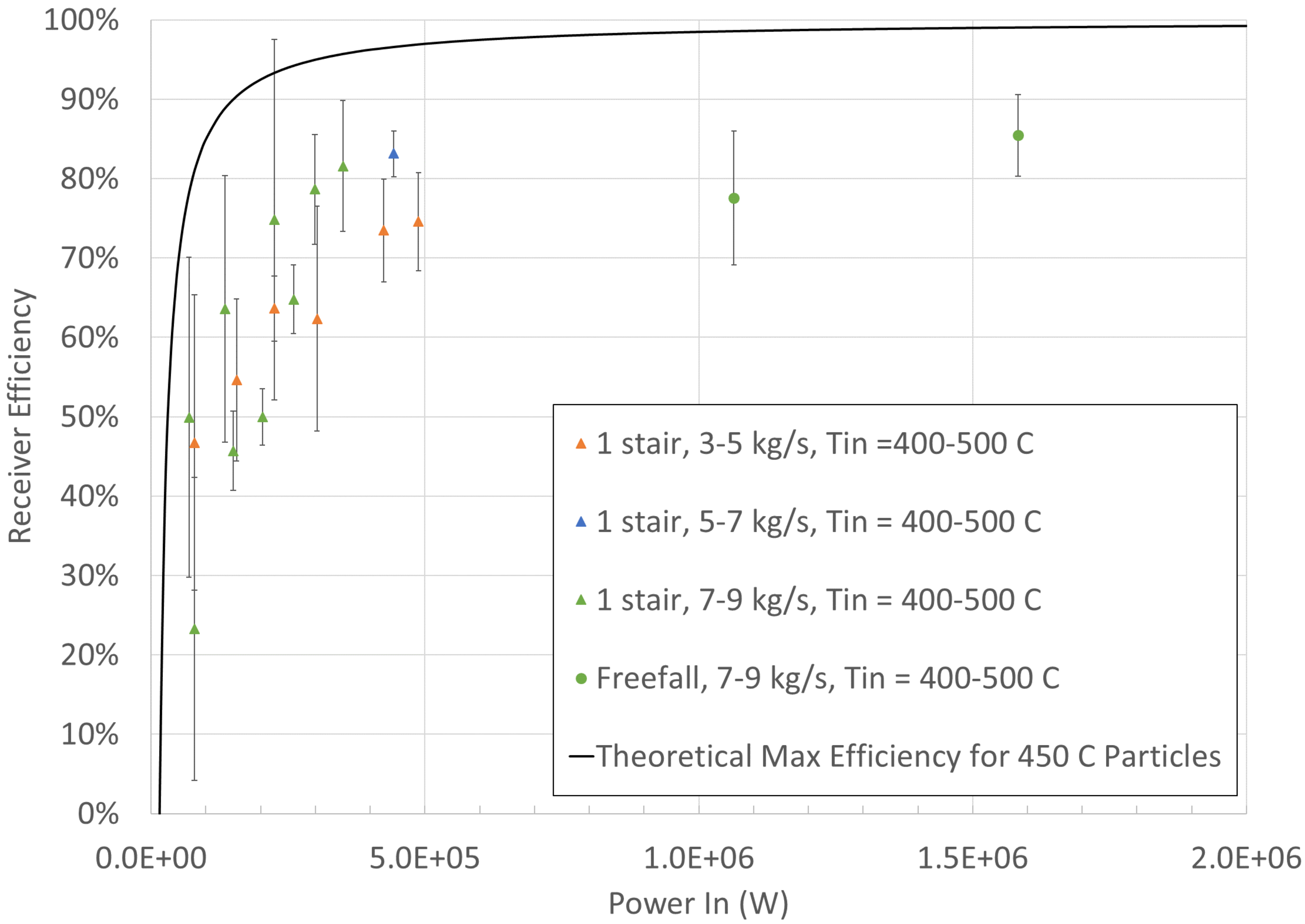
Sample of Test Log

Date	Start	End	Description	Weather
17-Aug-20	11h00	14h30	Receiver testing 500°C and 700°C, peak flux of 60 and 115 W/cm^2, two stairs	Very windy afternoon, Some clouds
18-Aug-20	11h00	14h30	Receiver testing 500°C and 700°C, peak flux of 60 and 115 W/cm^2, two stairs	Hazy from smoke
20-Aug-20	10h30	15h00	Test load cells, 50 W/cm^2, 500-600 °C, test single stair, top stair only	
21-Aug-20	10h30	14h00	Receiver testing, load cell troublehooting, single top stair	Hazy from smoke, low DNI
4-Sep-20	10h30	15h00	Receiver test day, 500C @ 5kg/s and 10 kg/s, with 50 W/Cm^2 700C @ ±5kg/s and 50 W/cm^2 700C at 108W/cm^2	Good DNI clear skies

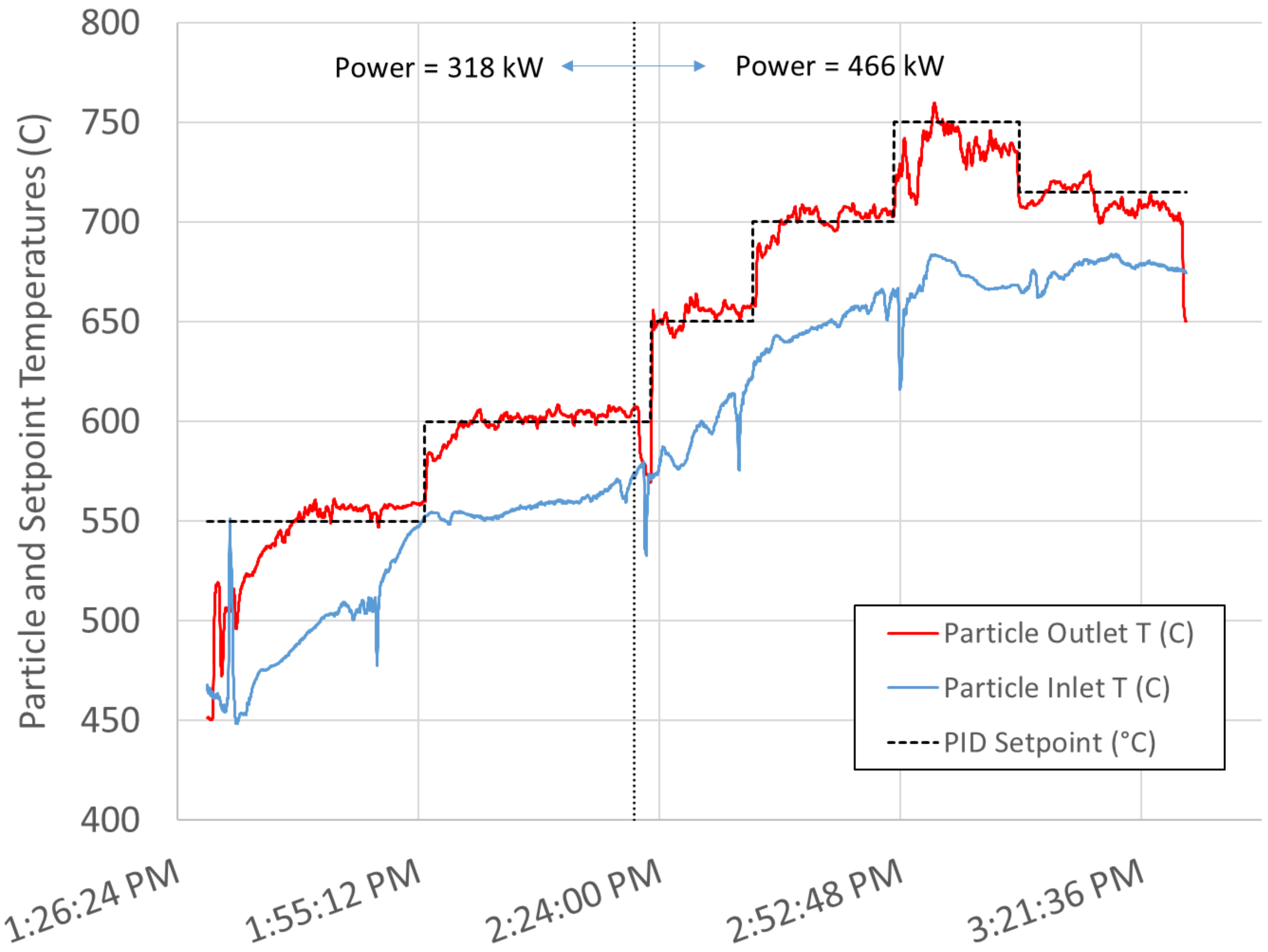
On-Sun Particle Temperatures



Receiver Efficiencies



Particle Temperature Control



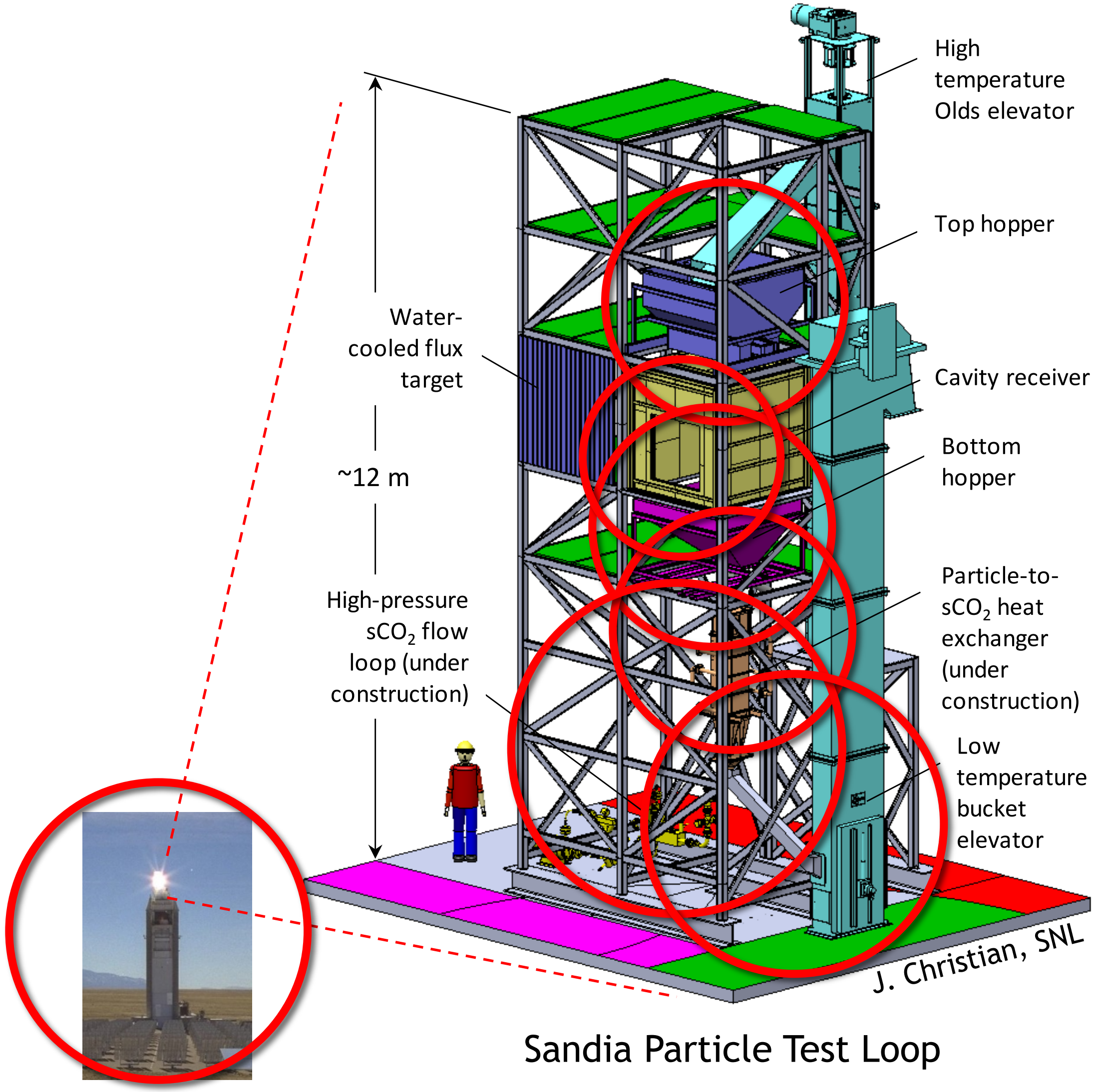
- Automated particle outlet temperature control using closed-loop PID controller

Overview

- Introduction and Objectives
- Receiver Design
- On-Sun Testing
- Lessons Learned

Mechanical Interfaces of System

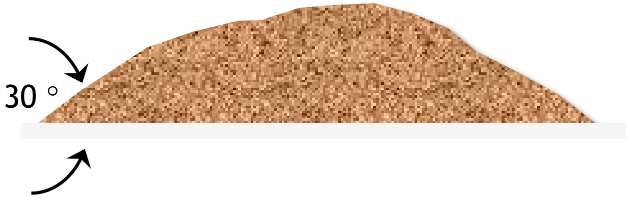
- Particle feed to the receiver
- Concentrated sunlight to particles
- Receiver to storage/collection bin
- Storage to heat exchanger
- Heat exchanger to sCO2 flow loop
- Heat exchanger to particle lift

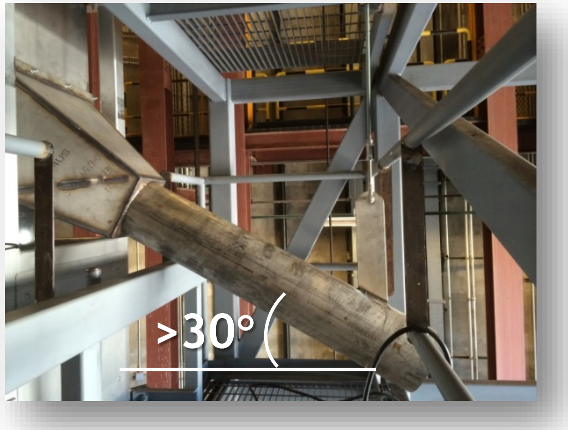


Sandia Particle Test Loop

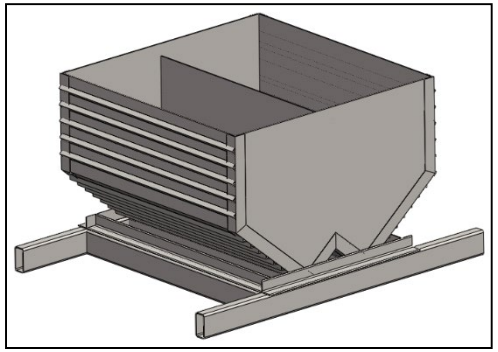
Particle Feed to the Receiver

- Sufficient pipe inclination angle for flow
  - Particle friction changes with temperature
- Funnel flow and avalanching in top hopper

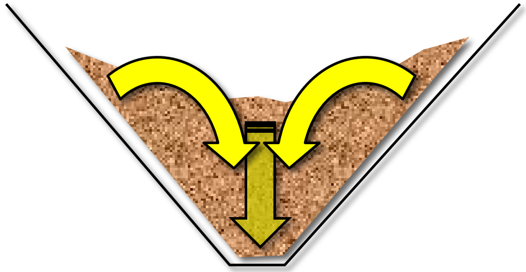




Pipe from particle elevator to top hopper



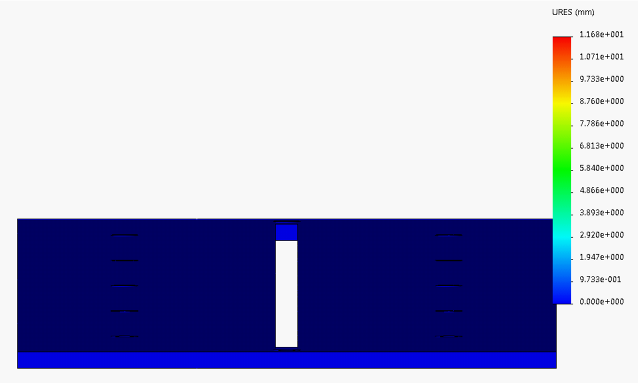
Top hopper

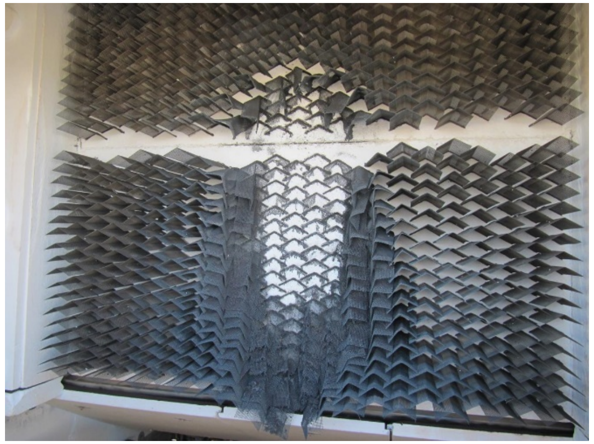


Funnel flow and avalanching

Particle Feed to the Receiver

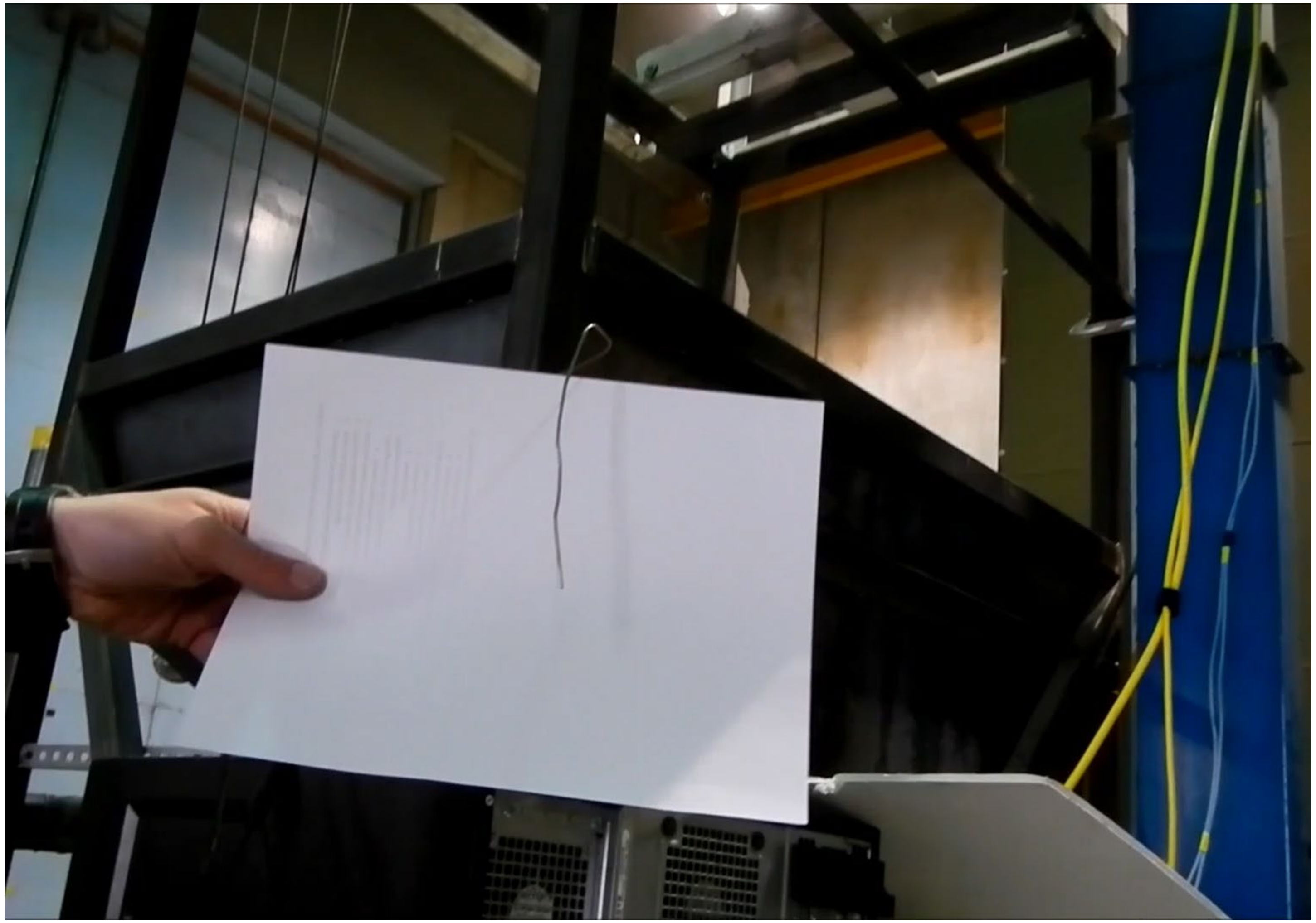
- Initially used fixed-aperture plates to control mass flow rate into receiver
- Slotted plate deformed upon heating
- Reduction of particle mass flow rate led to melting of mesh structures
- Need automated particle mass-flow control to maintain constant particle outlet temperatures with varying irradiance





Staggered array of chevron-shaped mesh structures

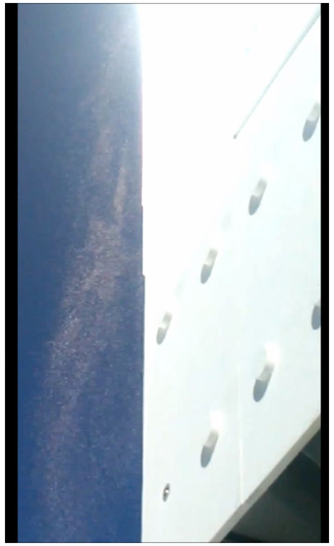
Particle Mass Flow Control - Demo



G. Peacock, K. Albrecht (SNL)

Concentrated Sunlight to Receiver

- Particle loss through open aperture
  - Trade-off between direct irradiance and particle losses
- Air curtains to reduce convective heat loss
- Light trapping with novel particle release patterns

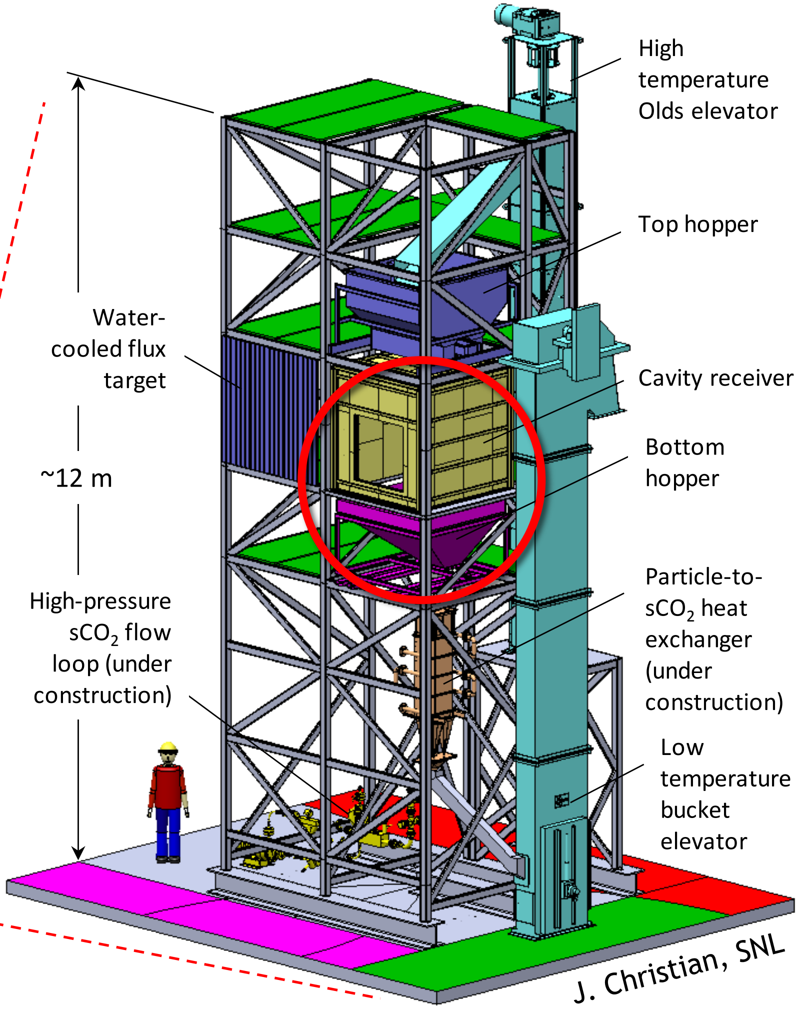


Nov. 2, 2015
3/8” slot - free fall
280 micron ACCUCAST
ID50
10-15 mph south wind
500 - 1000 suns

Pump and nozzles to produce air curtain across aperture

Receiver to Storage Bin

- Reduce wear from direct impact on walls
    - Design for particle to particle impact
- Minimize opening to reduce heat loss from storage
- Design for filtration of debris and particle fines



Sandia Particle Test Loop

Summary

Summary

- Next-generation high-temperature particle receiver designed and tested
  - Optimized geometry to reduce advective and particle losses
  - SNOUT wind protection
  - Stairs to increase particle-curtain opacity and stability
- Lessons learned
  - Designs need to be scalable to large sizes (~1000 kg/s required)
  - High-flux, high-temperature environments are harsh on materials and sensors
    - In-situ measurements of temperature, mass flow, irradiance, wind
  - Thermal expansion
  - Mass flow control
  - Transient operation (start-up and shut-down)

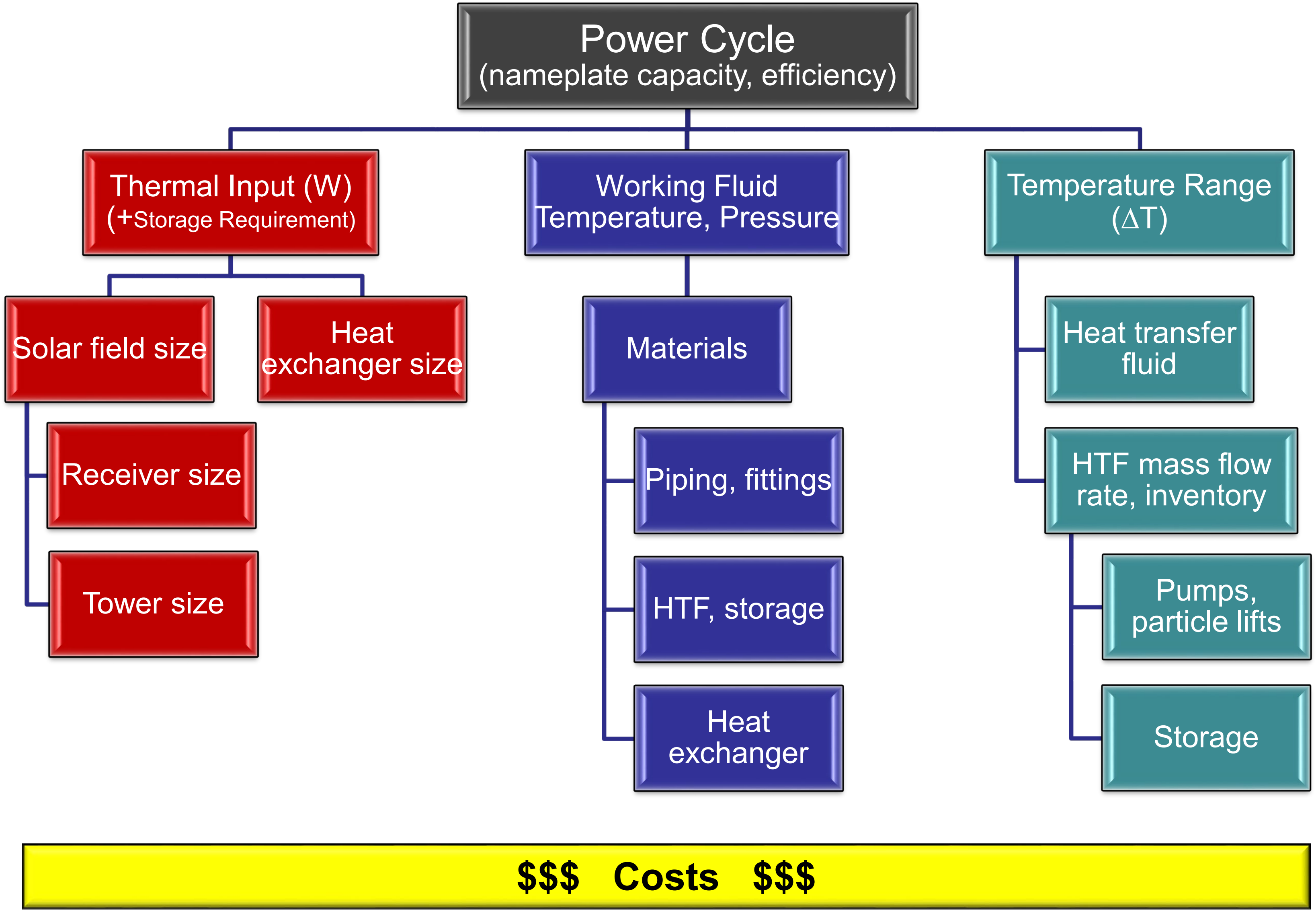
Acknowledgments

SOLAR ENERGY
TECHNOLOGIES OFFICE
U.S. Department Of Energy

- 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, Vijay Rajgopal, and Shane Powers

Backup Slides

Thermodynamic Interfaces



Power Cycle
(nameplate capacity, efficiency)

Thermal Input (W)
(+Storage Requirement)

- Solar field size
  - Receiver size
  - Tower size
- Heat exchanger size

Working Fluid Temperature, Pressure

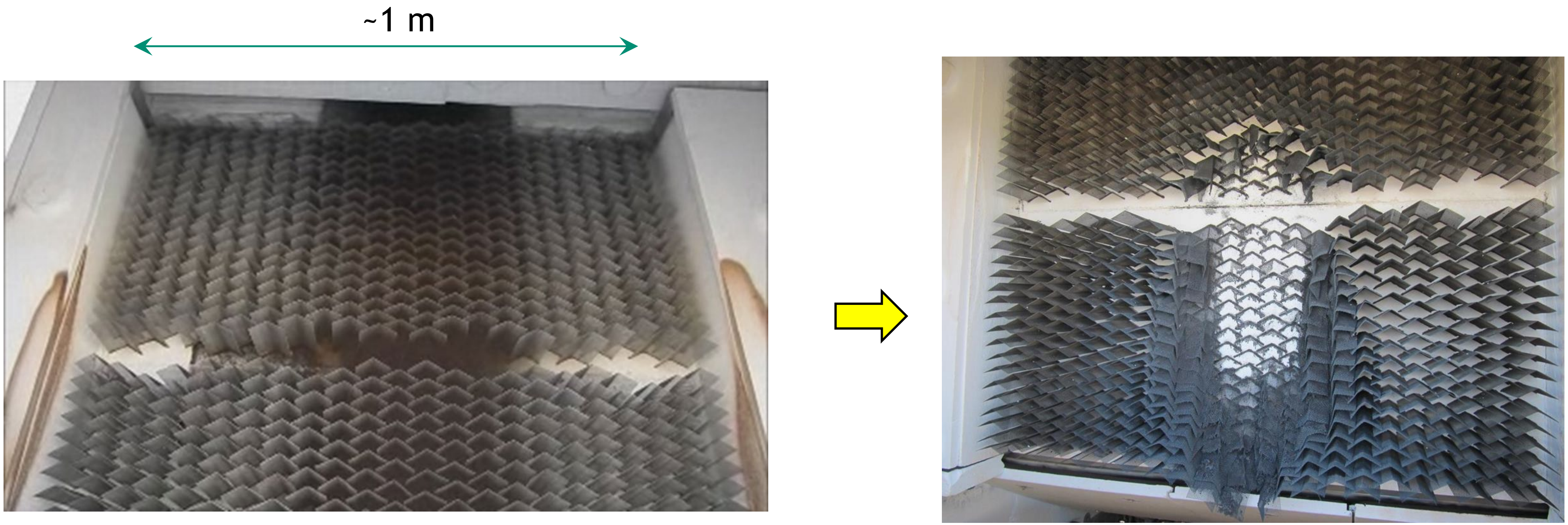
- Materials
  - Piping, fittings
  - HTF, storage
  - Heat exchanger

Temperature Range
(ΔT)

- Heat transfer fluid
- HTF mass flow rate, inventory
  - Pumps, particle lifts
  - Storage

$$$ Costs $$$

Overheating of Flow Obstructions



Failure of 316 SS mesh structures on July 24, 2015
~700 suns at ~1000 C (steel)

Uneven particle flow caused runaway heating and melting of obstructions

BraytonEnergy

Innovations Enabling *a* Gen3 Gas-Phase Receiver

29 October 2020

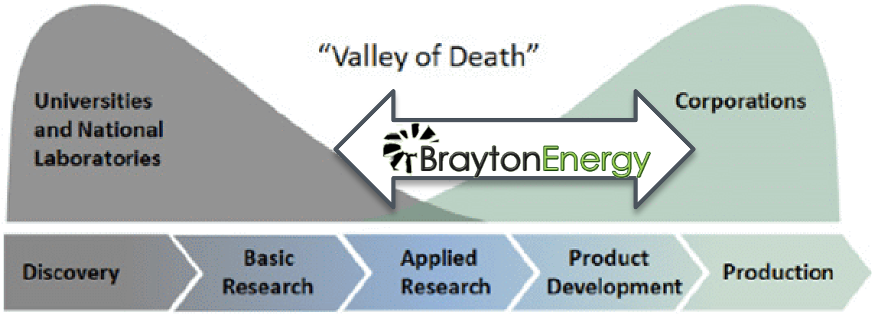
Shaun Sullivan
Principal Investigator, Gen3 Gas Phase
Renewables R&D Program Manager
sullivan@braytonenergy.com

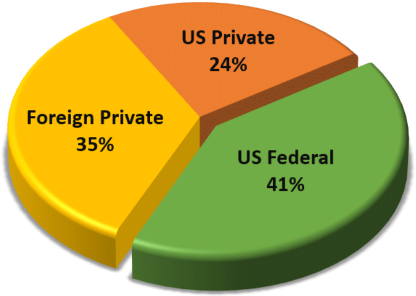
Introduction • Receiver Tour • Flux Profiling • Emerging Materials • System Optimization

BraytonEnergy

an innovative R&D firm dedicated to making meaningful contributions in the field of environmentally responsible, sustainable energy production

- Turbomachinery
- Compact Heat Exchangers
- Distributed Generation/CHP
- Concentrating Solar
- Alternative Fuels
- Energy Storage
- Hybrid Vehicles
- Nuclear
- Combustion
- UAVs

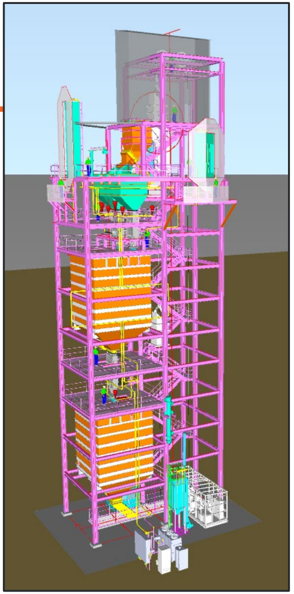




2019-2020

Gen3 Gas Phase System

- Develop a 100 MW_e commercial system that can absorb, store, and dispatch concentrated solar energy to a working fluid at conditions commensurate with an sCO_2 power cycle (700 °C, 25 MPa)
- Design a Megawatt-scale test facility to demonstrate and de-risk the technology innovations embodied in the commercial design

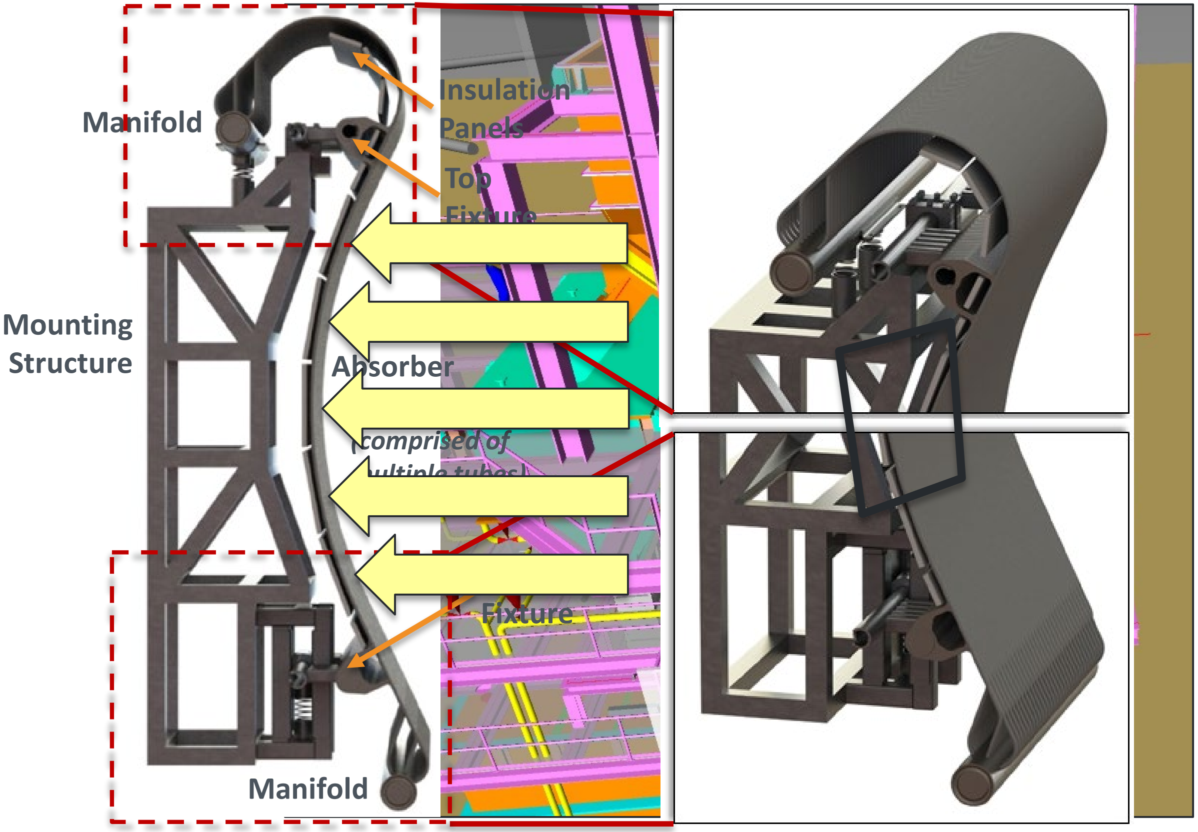


✓ Phase 1 (October 2018-December 2019)
  - System specification, design, modeling, analysis
- Phase 2 (January 2020-March 2021)
  - Component-level testing
  - Test facility design
- Phase 3 (October 2021-October 2024)
  - Test facility final design, construction, commissioning, operation, and testing

BraytonEnergy

NREL NATIONAL RENEWABLE ENERGY LABORATORY
Worley energy | chemicals | resources
Advisian Worley Group
BrightSource
COLORADO SCHOOL OF MINES
DLR
ECHOGEN power systems
EPRI
GREG MEHOS PH.D., P.E.
Heliogen
SolarDynamics
SolarTAC Technology Acceleration Center
SOLEX THERMAL SCIENCE
Southwest Solar Technology LLC
WISCONSIN UNIVERSITY OF WISCONSIN-MADISON

A Quick Tour: Gen3 Gas Phase Receiver



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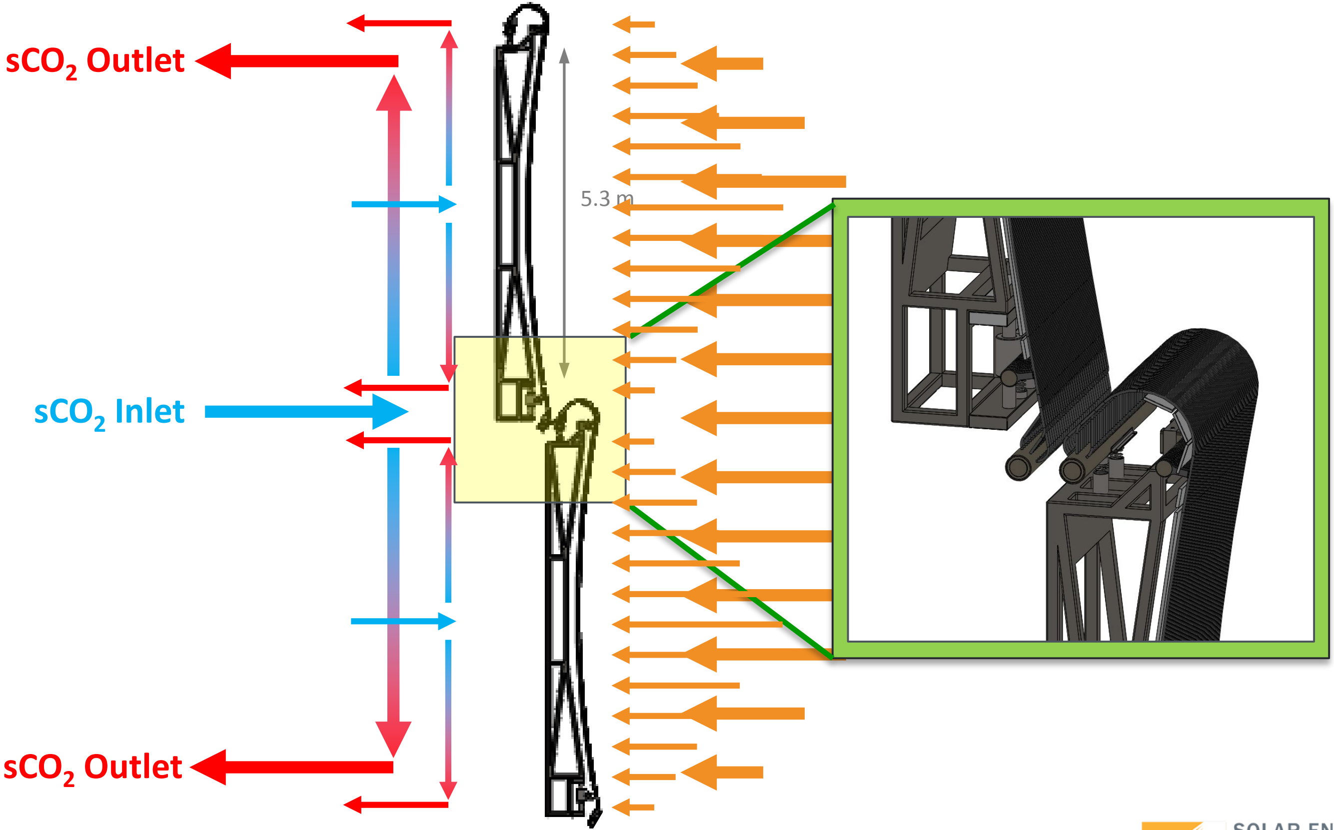
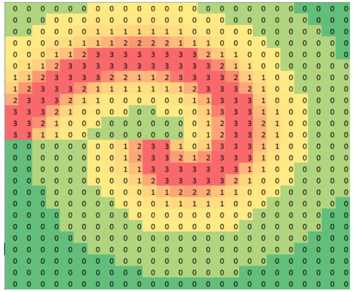
Maximizing the Utilization of Materials



Flux Profiling

Desired (Prescribed) Flux



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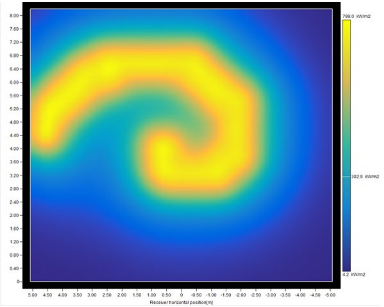
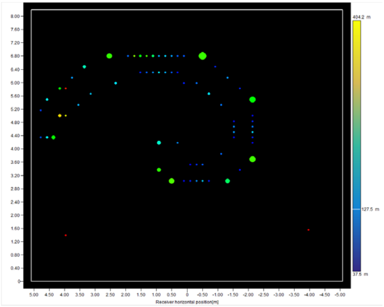
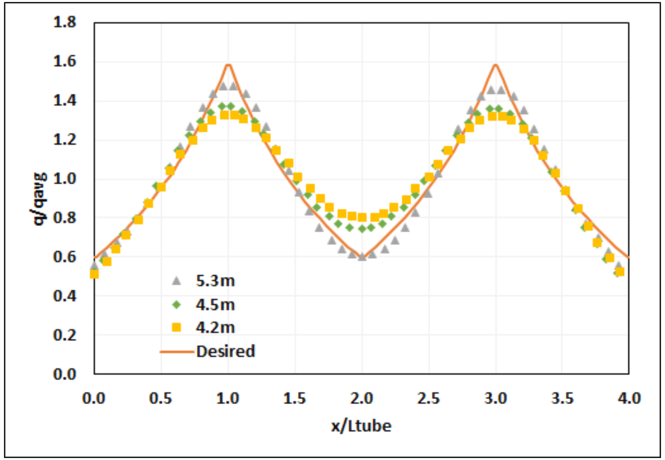
Simulated Flux



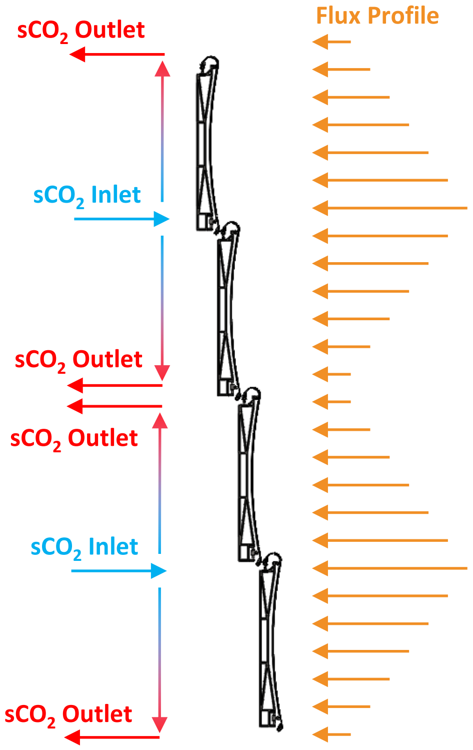
Aimpoints





- Aim point selection incorporated into GEN3 system
  - Selection based on matching a prescribed user flux profile
- Ability to achieve desired flux profile depends on complexity of desired profile for:
  - Given heliostats (optical errors)
  - Receiver geometry
  - Field size

Innovative Heliostat Field Control



sCO$_2$ Outlet

sCO$_2$ Inlet

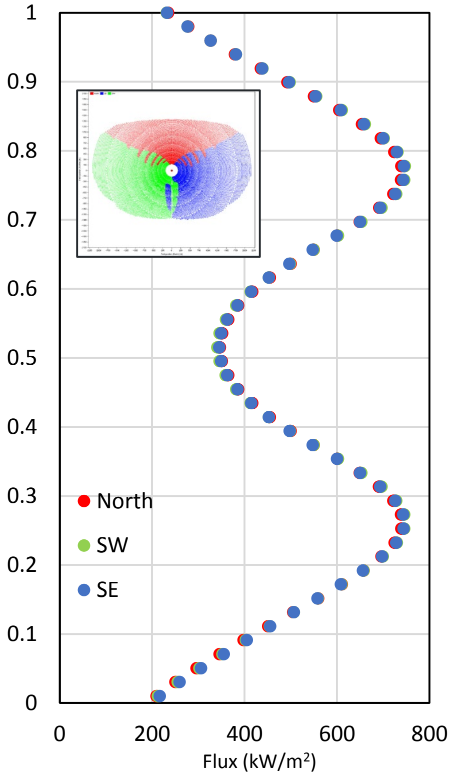
sCO$_2$ Outlet

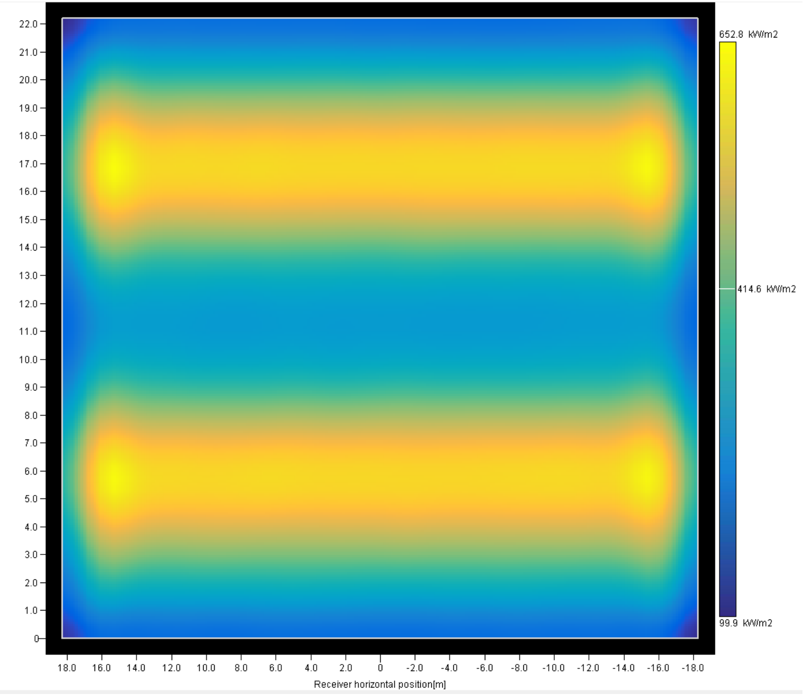
sCO$_2$ Outlet

sCO$_2$ Inlet

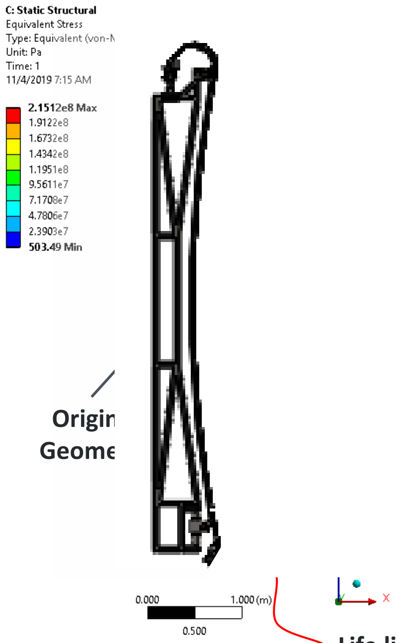
sCO$_2$ Outlet

Flux Profile





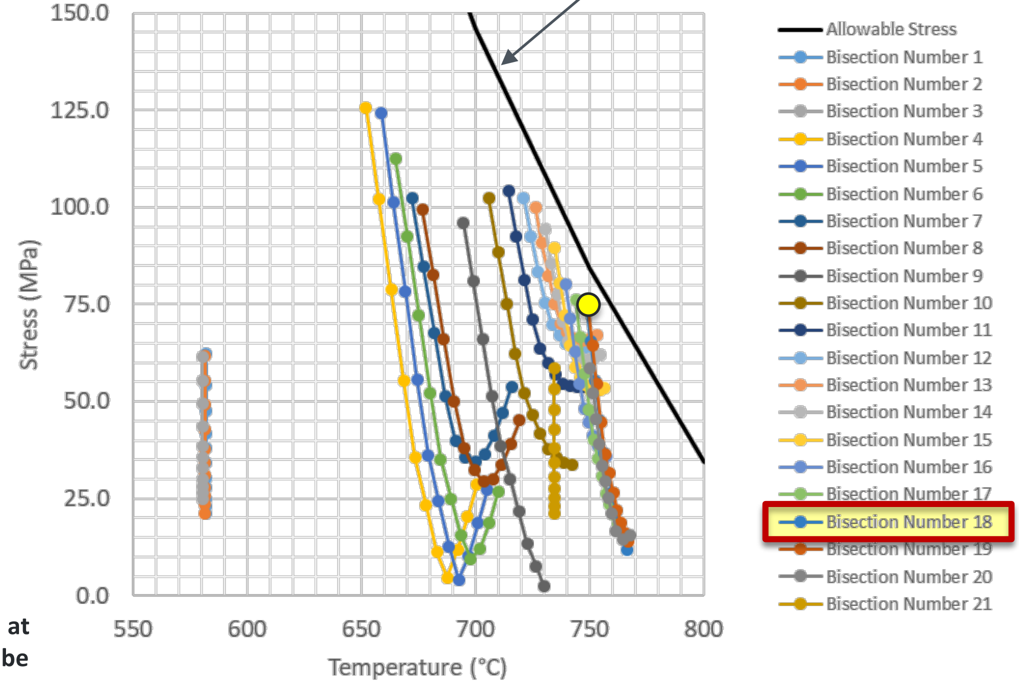
Single Tube Structural Model Results



Origin
Geome

Life limiting location at hottest section of tube

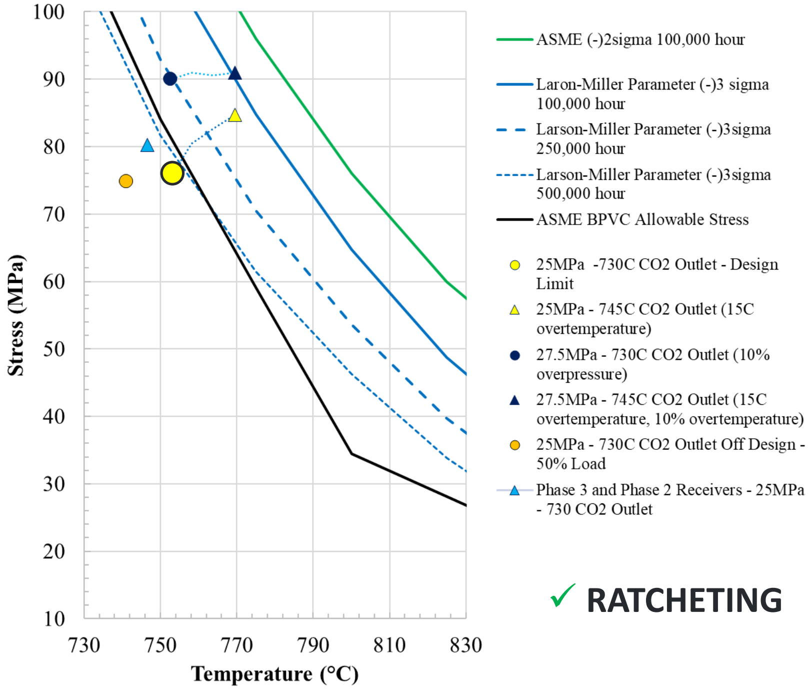
ASME Section II Allowable Stress



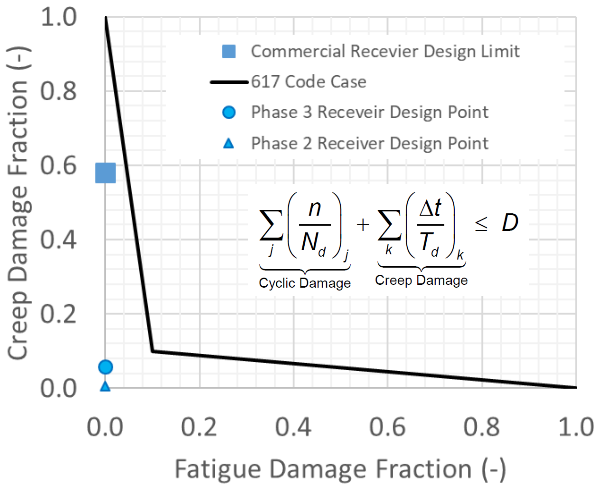
Receiver Life Results

✓ **PRIMARY LOAD** - Stress versus temperature

- *life limiting case*



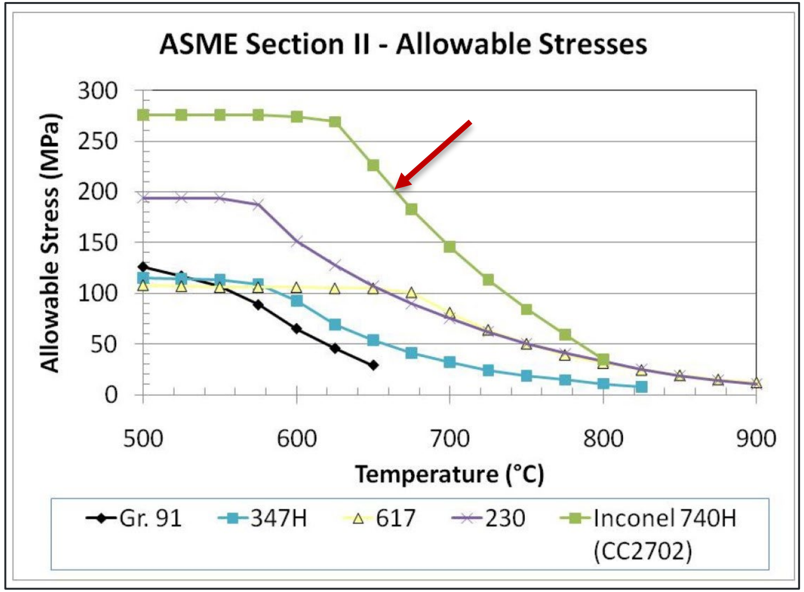
✓ **RATCHETING**

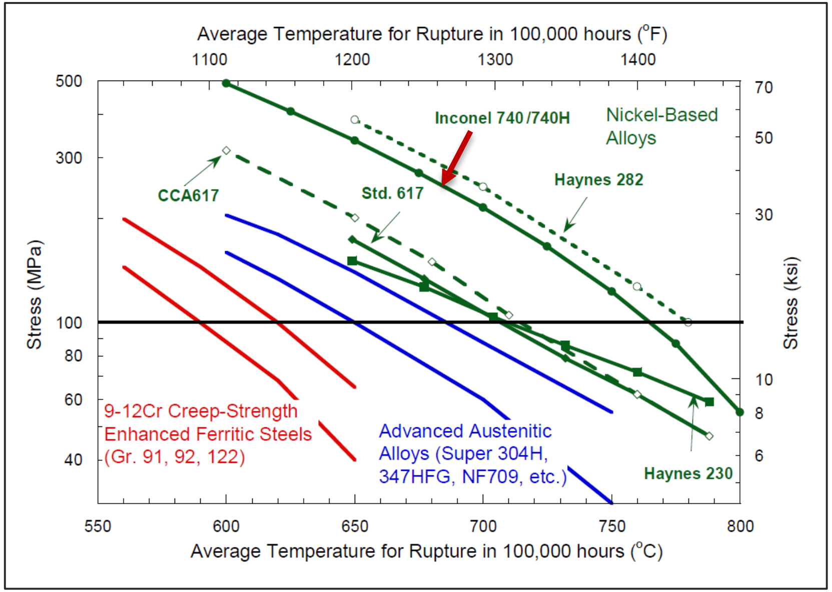


Parameter	Cycle Type 1 Start-up/ Shut-down	Cycle Type 2 Cloud Event
Elastic strain range, Δεe	0.000375	0.00019
Creep strain per cycle, Δεc	1.72987E-07	0
Total strain range, $\Delta\varepsilon_T$	0.00061	0.00002
Design Allowable Cycles, Nd	5.22E+13	2.10E+15
Design Cycles, n	10950	109500
Cycle Damage Fraction	2.10E-10	5.22E-11
Total Fatigue Damage Fraction	2.6198E-10	

✓ **CREEP-FATIGUE**

Special Metals In740H

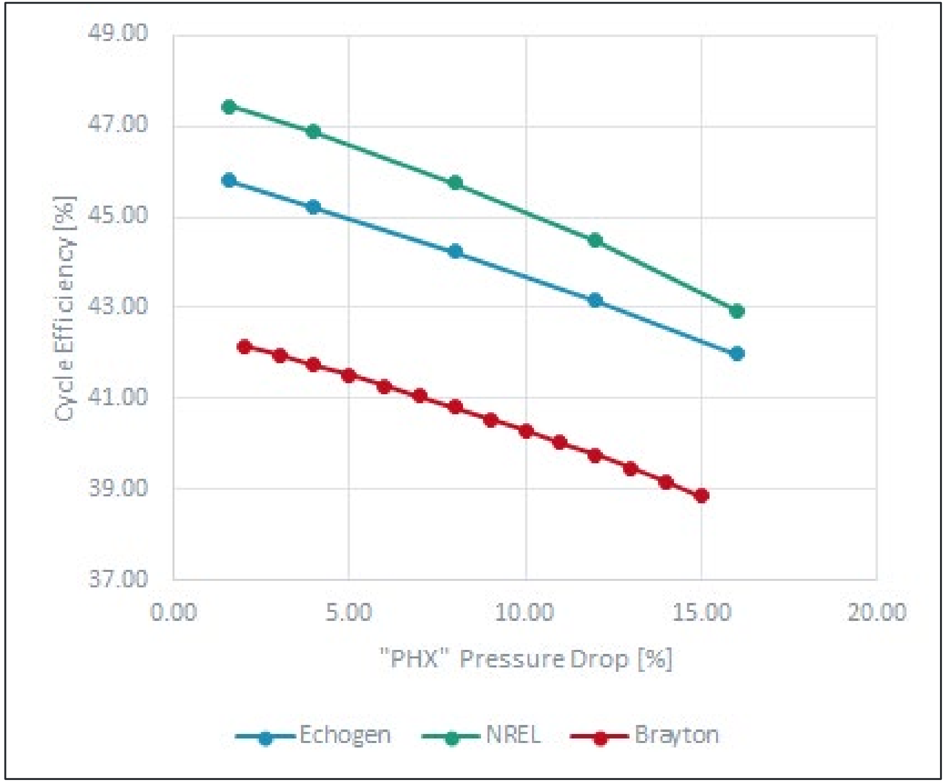




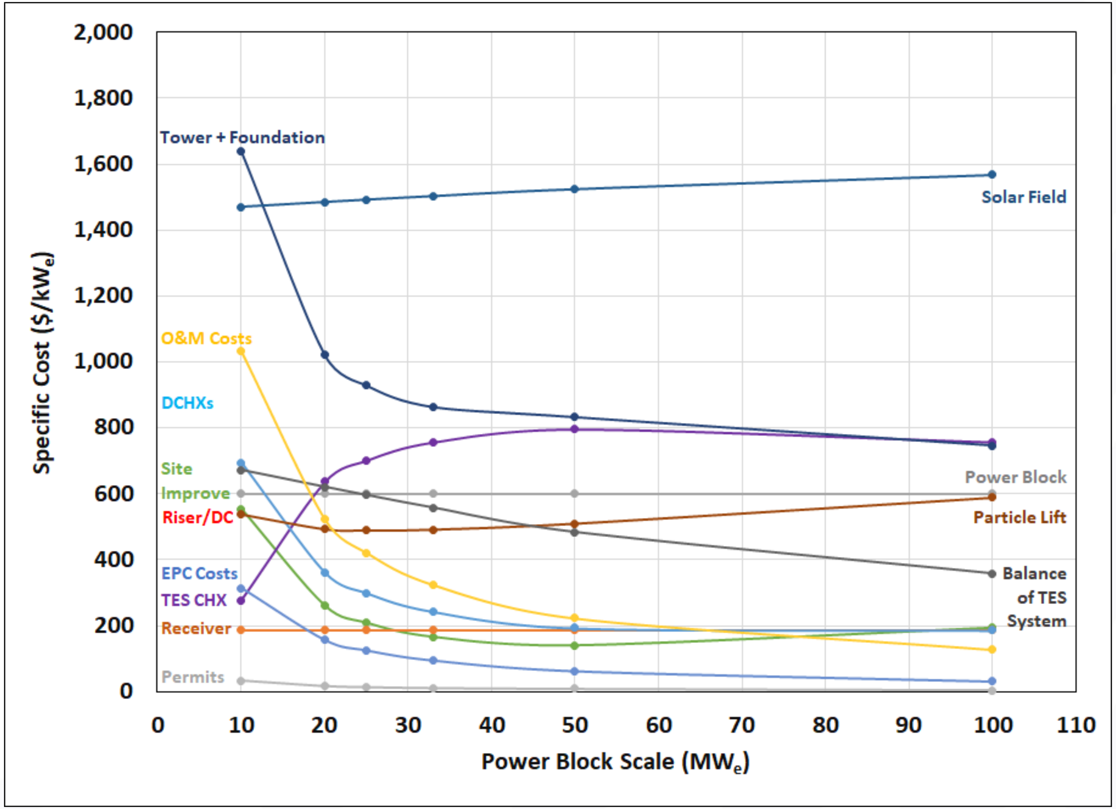
- *Receiver design entirely enabled by the advent of In740H*
  - *H282 is an even more promising prospect with active AM development, but is not yet code qualified*

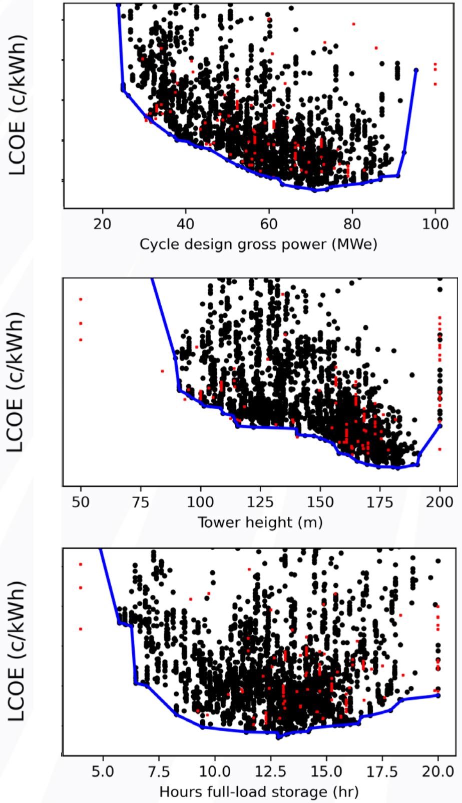
Integrated System Modeling

- The Gen3 Gas Phase leverages the baseload power block as the heat transfer fluid circulator during TES charging operation
  - Minimizes capital costs
  - Imposes a pressure drop penalty during on-sun operations
- Independent studies evaluated the impact of this pressure drop



LCOE Optimization and Specific Cost Functions

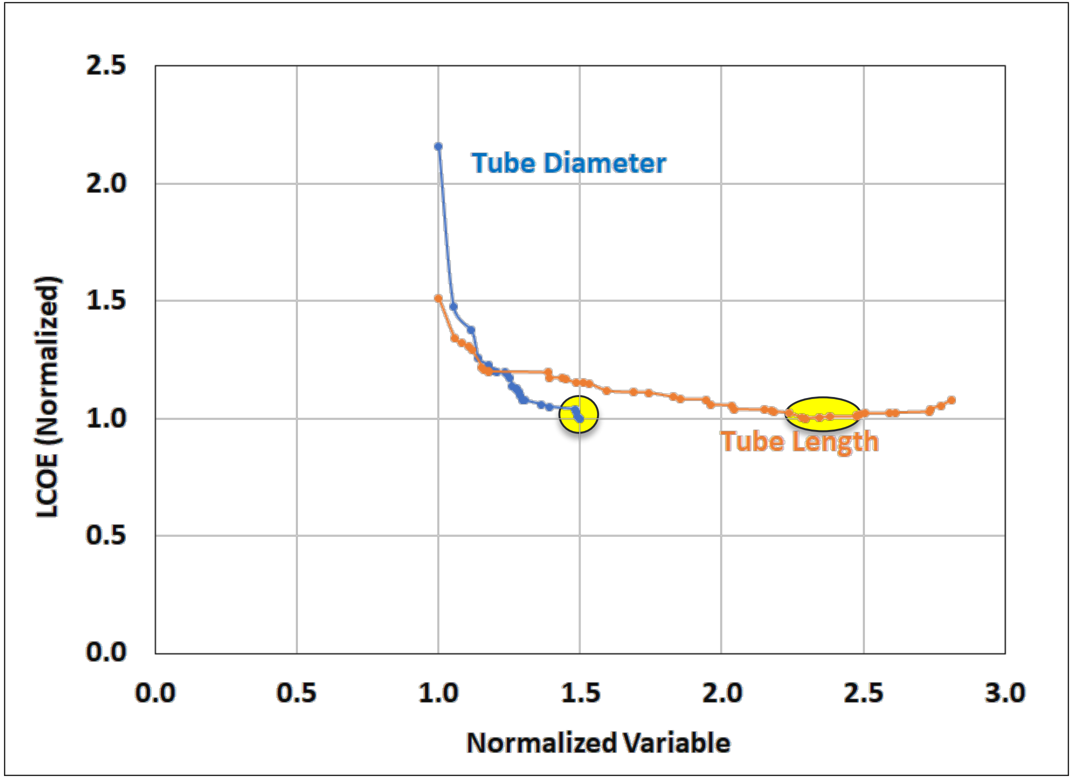




BraytonEnergy

Optimal *System* Design Accepts Elevated DP

- An integrated analysis that does not presuppose "foregone conclusions" can lead to non-intuitive results
  - i.e. LCOE is minimized by optimizing the power block around a high on-sun PHX DP/P, and allowing it to operate at low DP/P during off-sun hours
  - This strategy also enables system integration with AUSCS cycles, which are significantly less sensitive to PHX DP/P
- System stability demonstrated via detailed turbomachinery mapping and cycle analysis



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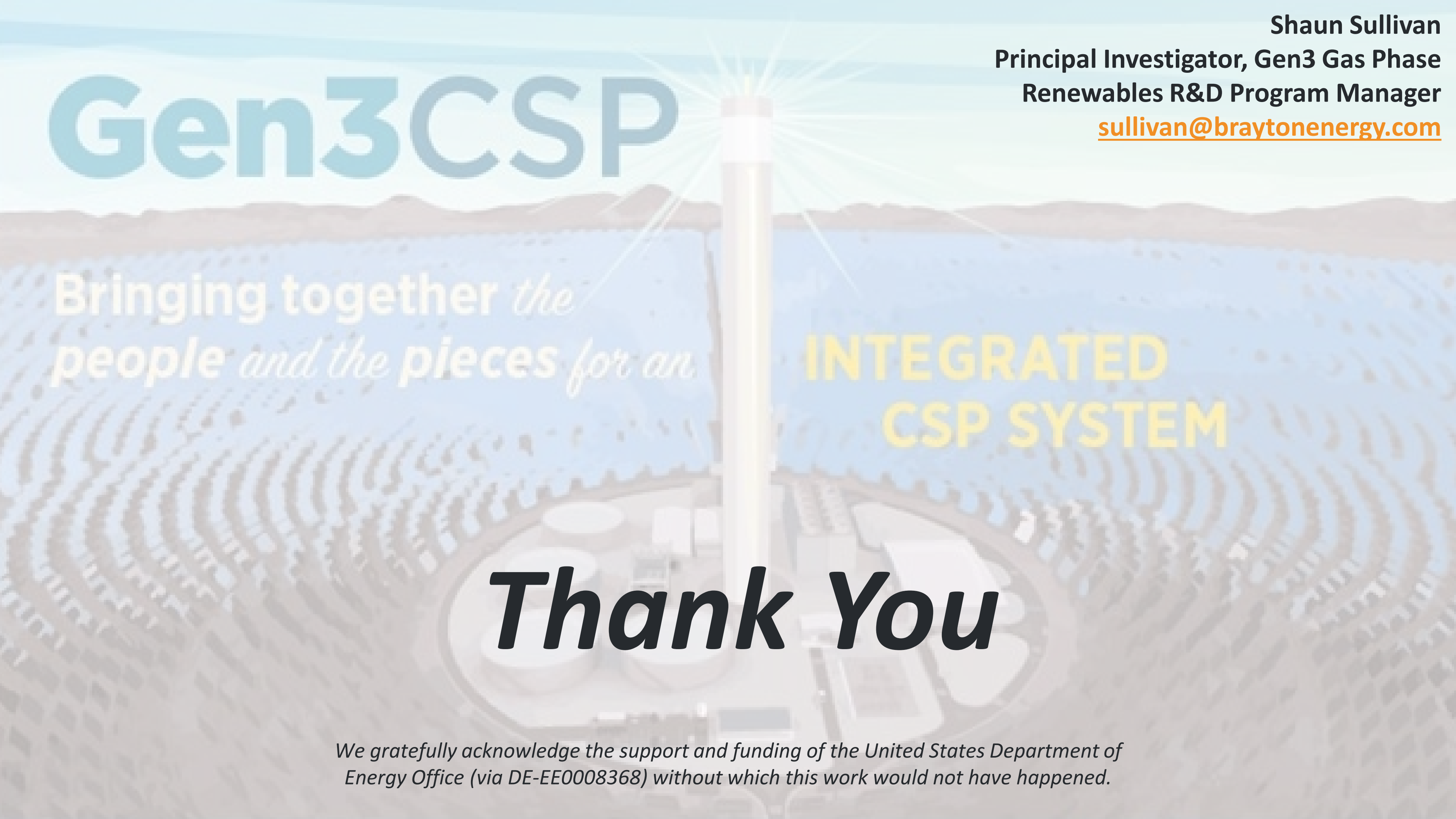

Thank You

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.

Liquid Pathway Receiver Design: Molten Salt and Liquid Sodium

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Thermal Energy Science & Technologies Group
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Crescent Dunes Solar Energy Facility, USA

Overview

- *Gen3 Liquid Pathway* project seeks to demonstrate potential of chloride-based molten salt for energy storage at > 700°C.
- Chloride salt's high freeze point and poor thermal conductivity are challenges for use in a solar receiver.
- Project evaluated molten chloride salt and liquid-metal sodium as alternatives for a liquid receiver at > 700°C operation.

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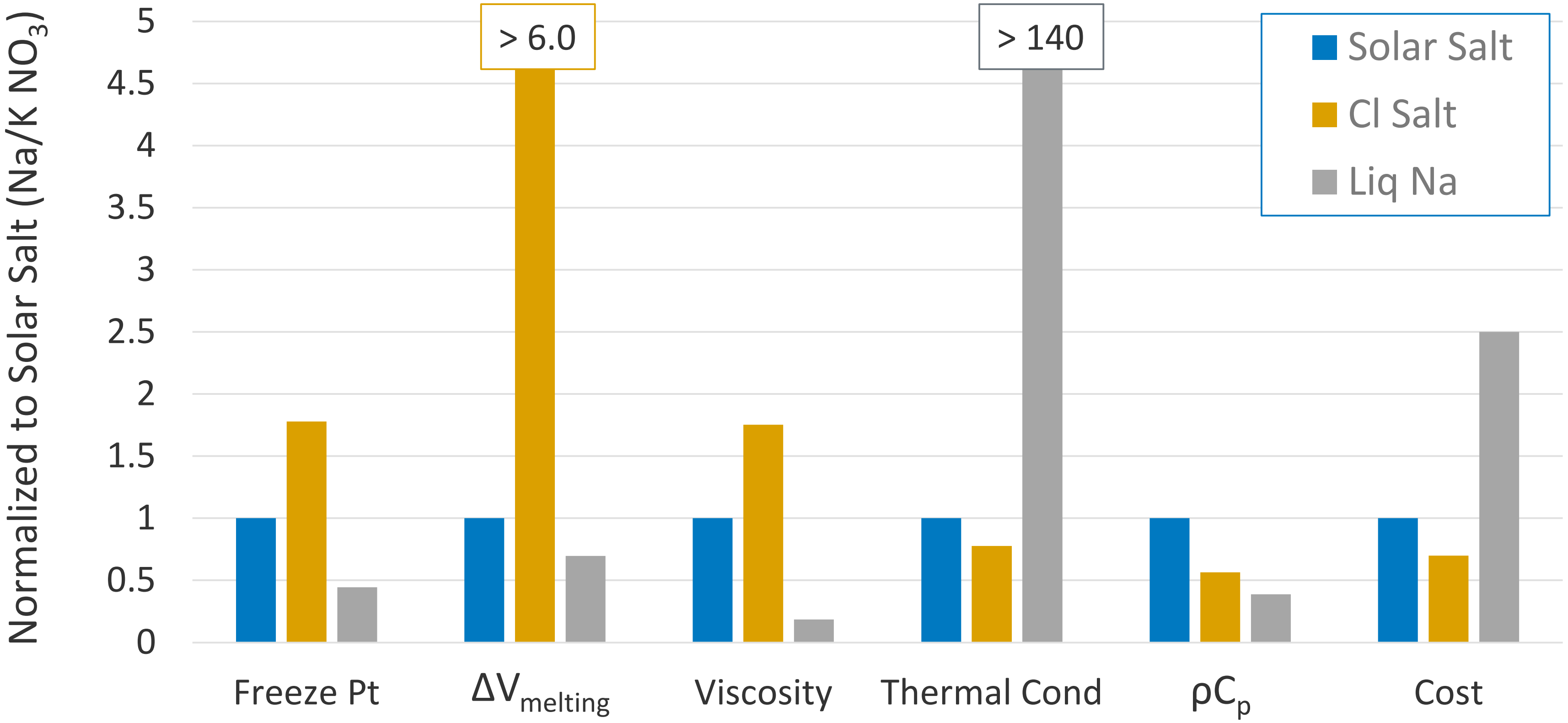
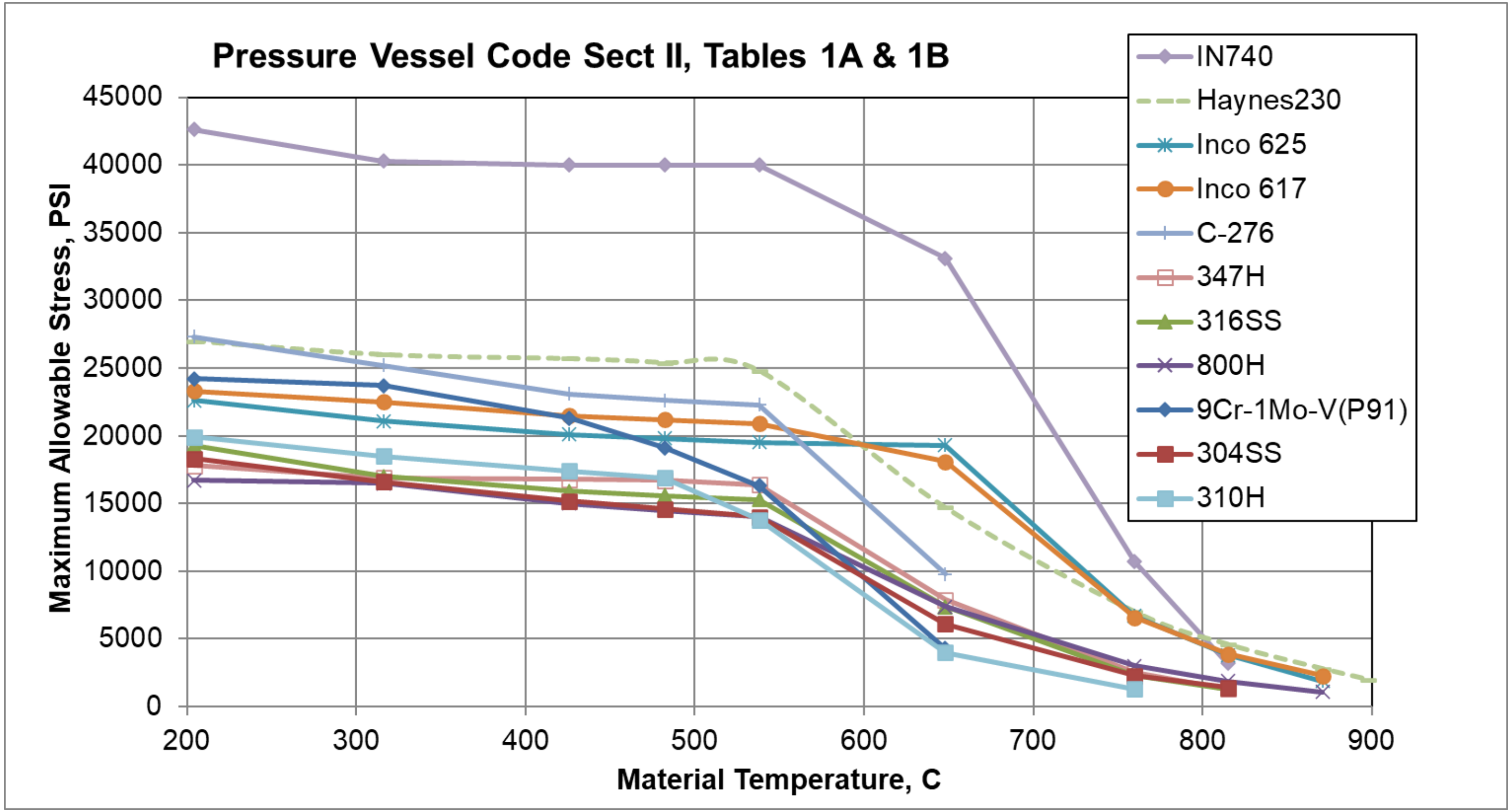
Research Institute

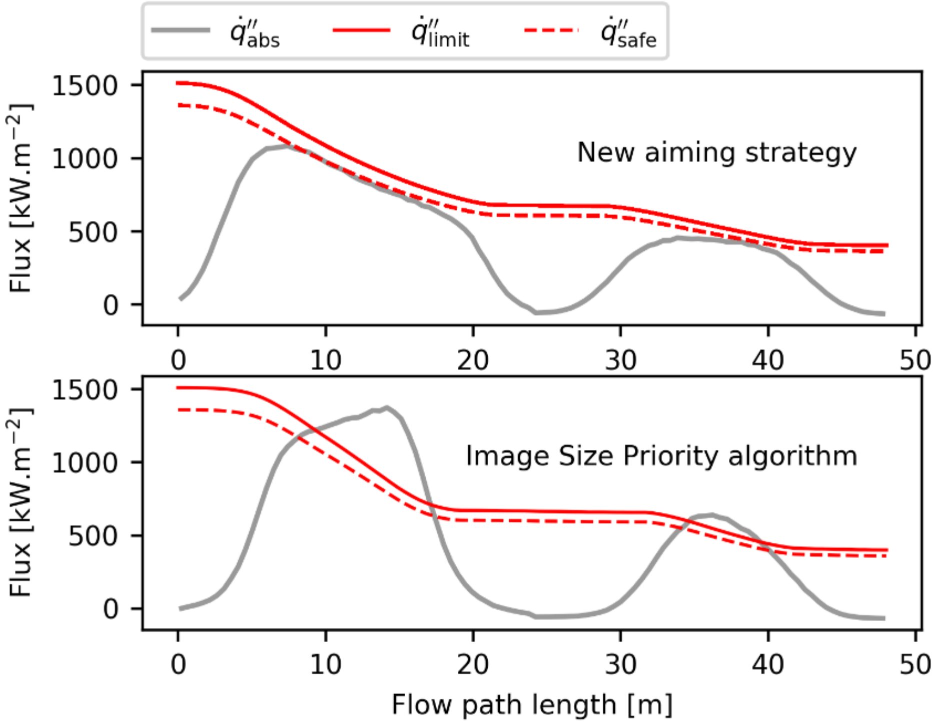
Gen3 Heat Transfer Fluids vs. Current Solar Salt

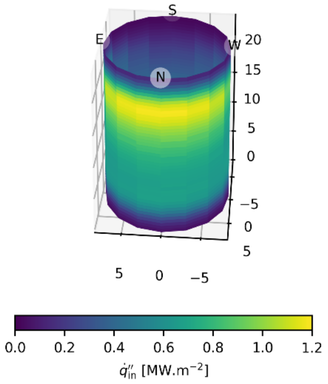


Alloy Strength with Temperature

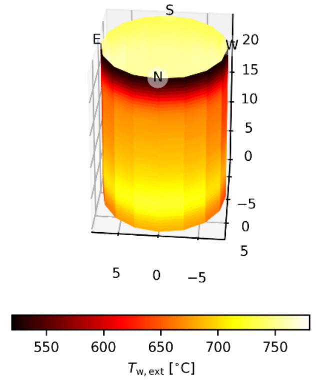


Critical to Maintain Flux within Allowable Limits





Flux Profile



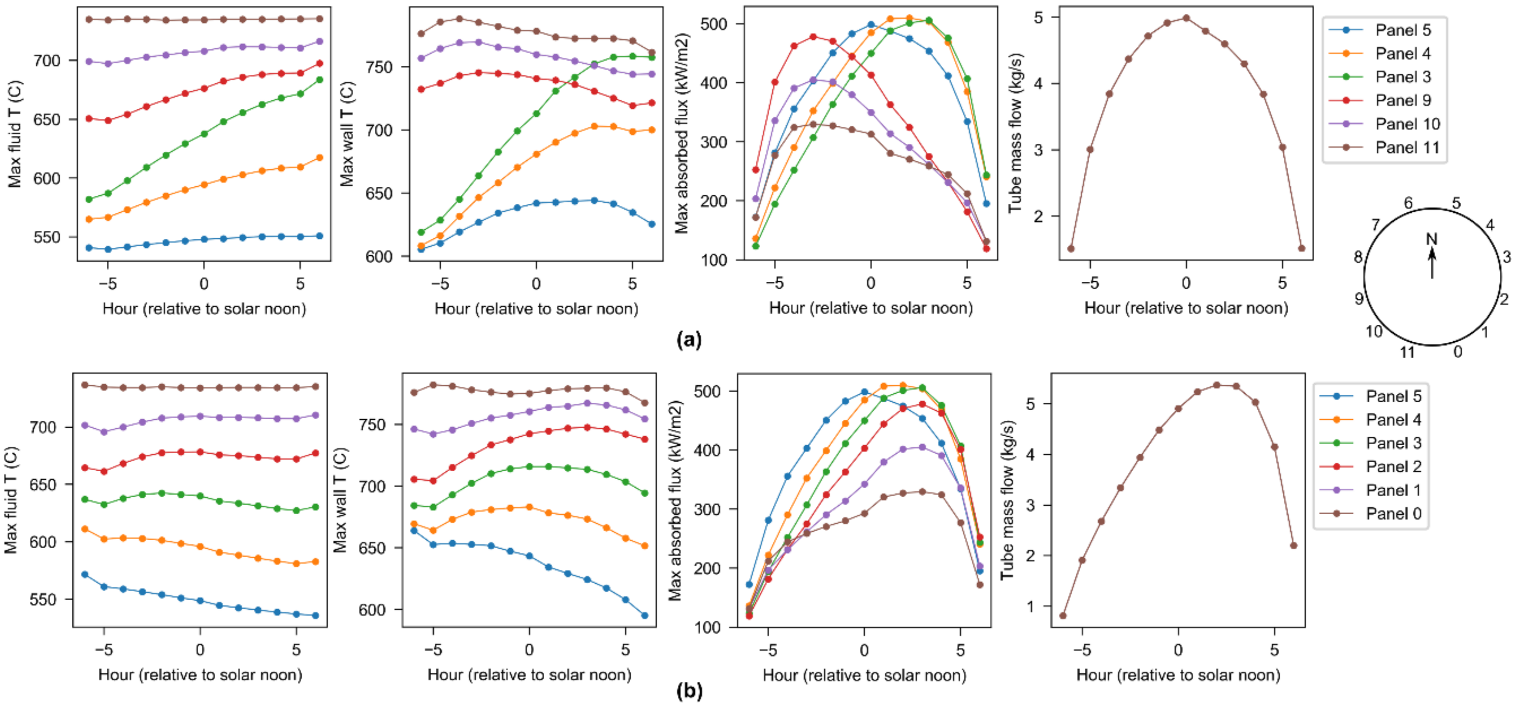
Temperature Profile

Rethink Conventions

Fluid Temp (°C) **Max Wall (°C)** **Max Flux (kW/m²)** **Tube Flow (kg/s)**

Conventional flow circuit spans panels (5, 4, 3, 9, 10, 11)

Bottom Row: Flow circuit spans panels (5, 4, 3, 2, 1, 0)

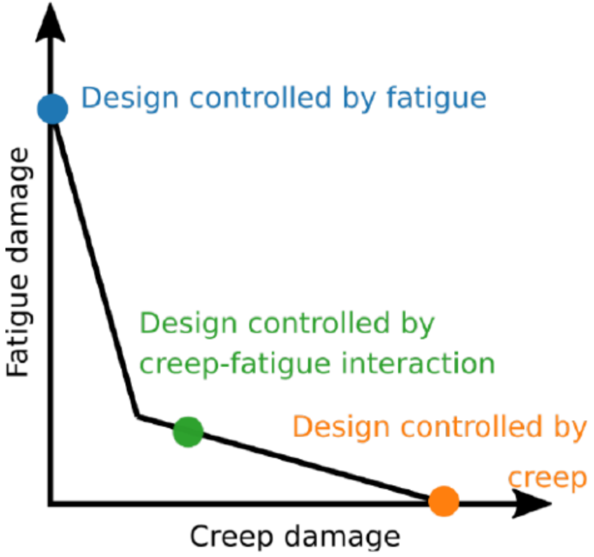


- ➢ *The bottom flow circuit limits the co-incidence of high-flux and high-temperature and the expected design life increases 5-6x versus the conventional (top) design.*

Creep / Fatigue Analysis

Solar Central Receivers:

- Aren't technically *pressure vessels* (no primary load)
- Diurnal cycling (of secondary load) means failure by:
  - Fatigue <600 °C
  - Creep-fatigue 600 °C to ≈750 °C
  - Creep ≈750 °C to 850 °C



Creep-fatigue damage diagram

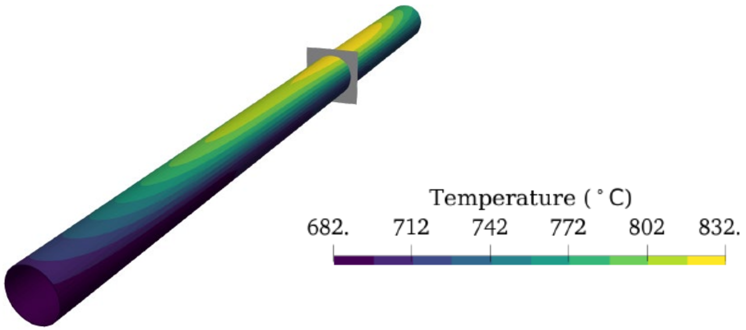
- Logie, "Structural Integrity of Advanced Solar Central Alloy 740H Receiver Tubes" SolarPACES 2020
- Bipul Barua et al., "Design Guidance for High Temperature Concentrating Solar Power Components," Argonne National Laboratory, Technical Report ANL-20/03, 2020.

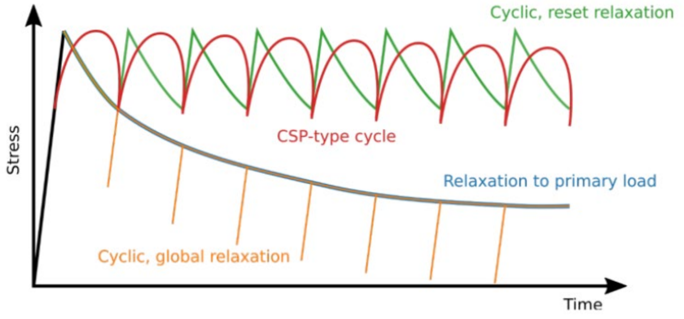
Design Methods for Creep-defined Systems

Simpler and conservative

More complex and more accurate

1. Design by elastic analysis using ASME Section III, Division 5
2. Design by elastic analysis using ASME Section III, Division 5 with reduced margin and simplified creep-fatigue evaluation
3. Design by inelastic analysis



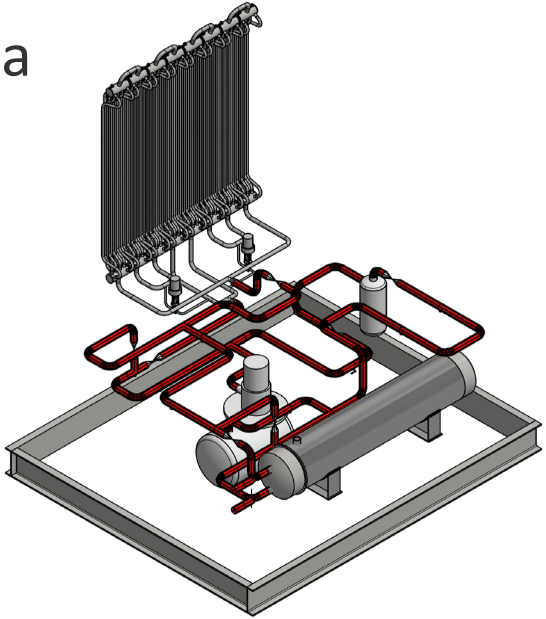


Loading histories

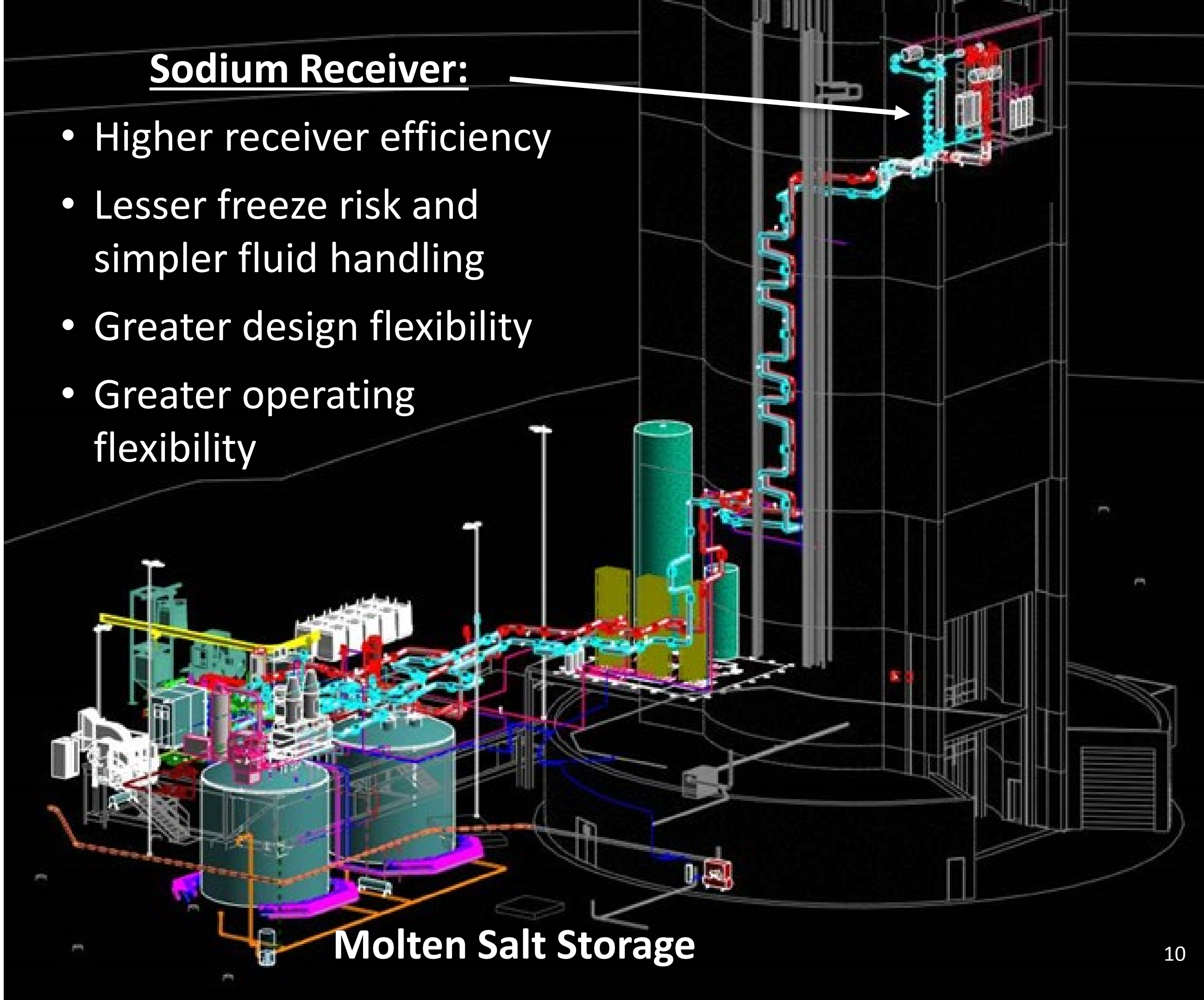
- Logie, “Structural Integrity of Advanced Solar Central Alloy 740H Receiver Tubes” SolarPACES 2020
- Bipul Barua et al., “Design Guidance for High Temperature Concentrating Solar Power Components,” Argonne National Laboratory, Technical Report ANL-20/03, 2020.

Pilot Scale Objectives

- Demonstrate operational control and reliability
  - Fill, control transients, drain, repeat
- Validate model results with performance data
  - Heat transfer coefficients
  - Temperatures (fluid and tube)
  - Ramp rate behavior
- Freeze recovery
- Corrosion rates and creep damage



Proposed Integrated System Design



Sodium Receiver:

- Higher receiver efficiency
- Lesser freeze risk and simpler fluid handling
- Greater design flexibility
- Greater operating flexibility

Molten Salt Storage

Summary

- Start with commercial design, use that to define what the pilot-scale system needs to do.
- > 700°C requires creep-regime analysis. Detailed inelastic analysis is necessary for accuracy and to avoid overly conservative limits.
- Material availability, code qualification, physical data, welding knowledge, etc. can be constraining.
- Transient operations will be the challenge.
- Rethink convention

Thank you!

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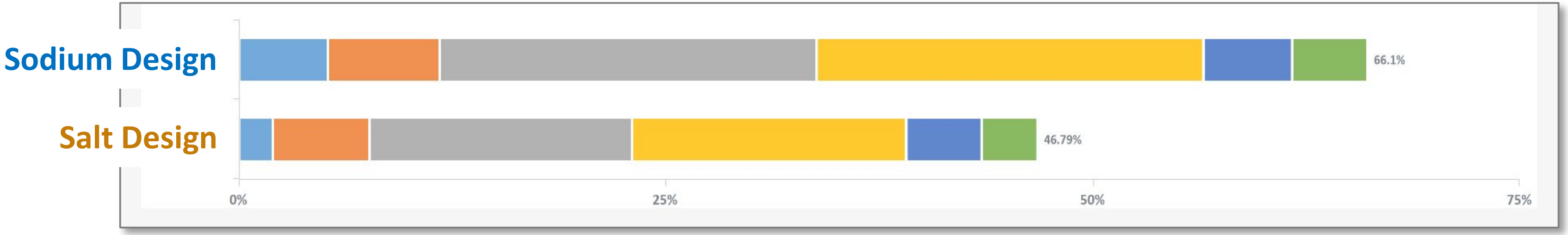
Supporting Slides

CSP Heat Transfer Fluids

Parameter	Solar Salt (Gen2)	Chloride Salt (Gen3)	Liquid Sodium (Gen3)
Composition	Binary $NaNO_3$-KNO_3	Ternary $MgCl_2$-KCl-NaCl	100% Na
Freezing Point (°C)	~238	~400	98
Volume change on melting	+3.3%	+20%	+2.6%
Stability Limit (°C)	~600	> 900	882 (bp)
Density (kg/m^3)	1770 @ 500°C	1560 @ 700°C	835 @ 700°C
Specific Heat (J/g-K)	1.53 @ 500°C	0.98 @ 700°C	1.26 @ 700°C
Viscosity (cP)	1.30 @ 500°C	2.28 @ 700°C	0.24 @ 700°C
Thermal Cond. (W/m-K)	0.54 @ 500°C	0.42 @ 700°C	64.2 @ 700°C
Major Concerns	NO_x formation Thermal stability	High freeze point Corrosion	Burns in air

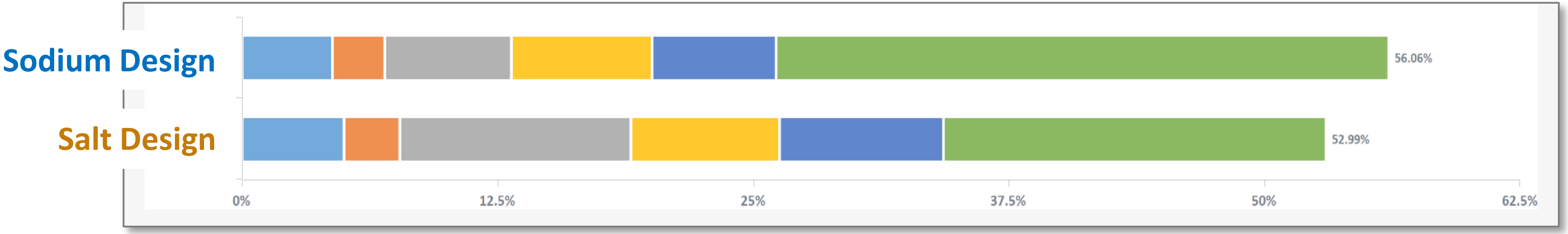
Benefit Scoring
(Higher Scores = Higher Benefit)



Criteria Legend

- Accommodate different plant sizes and configurations
- Maximize ease of operations and maintenance
- Maximize efficiency and performance
- Maximize long-term reliability and availability
- Maximize stakeholder support
- Minimize the time required to transition from the pilot phase demonstration to large-scale plants

Risk Scoring
(Higher Scores = Higher Risk)



Criteria Legend

- Minimize the risk of manufacturing issues
- Minimize the risk of a schedule delay
- Minimize the risk of design issues specific to the solar receiver
- Minimize the risk of obtaining bank financing and insurance for a commercial plant
- Minimize the risk of unplanned outages due to operational instability
- Minimize the risk to people and the environment

- Sodium case estimated at 11% lower LCOE
- Sodium case had better Benefit/Risk ratio: Sodium = 1.19, Salt = 0.86

➢ ***Team selected the Sodium Receiver design***

Oregon State University

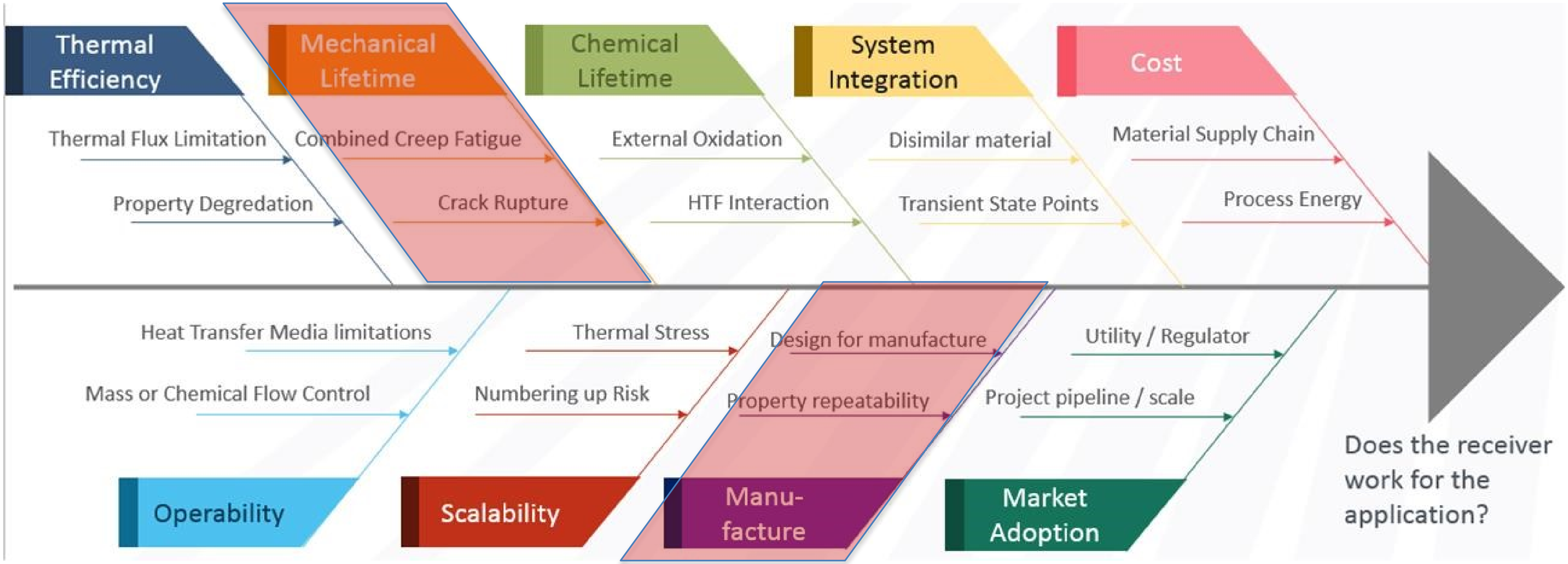
Impactful R&D for Technology Adoption

Brian M. Fronk
Solar Technology Office CSP R&D Virtual Workshop Series
October 29th, 2020

COLLEGE OF ENGINEERING

School of Mechanical, Industrial, and Manufacturing Engineering

Scaling Innovations



Thermal Efficiency
- Thermal Flux Limitation
- Property Degredation

Mechanical Lifetime
- Combined Creep Fatigue
- Crack Rupture

Chemical Lifetime
- External Oxidation
- HTF Interaction

System Integration
- Disimilar material
- Transient State Points

Cost
- Material Supply Chain
- Process Energy

Operability
- Heat Transfer Media limitations
- Mass or Chemical Flow Control

Scalability
- Thermal Stress
- Numbering up Risk

Manu-facture
- Design for manufacture
- Property repeatability

Market Adoption
- Utility / Regulator
- Project pipeline / scale

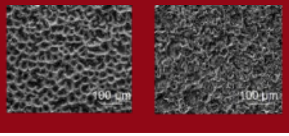
Does the receiver work for the application?

Context

Modular, micro-pin receivers can enable high efficiency and high temperature solar processes, but with significant manufacturing challenges.

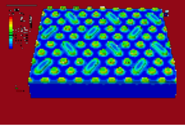
Separate Effects Investigation

Materials

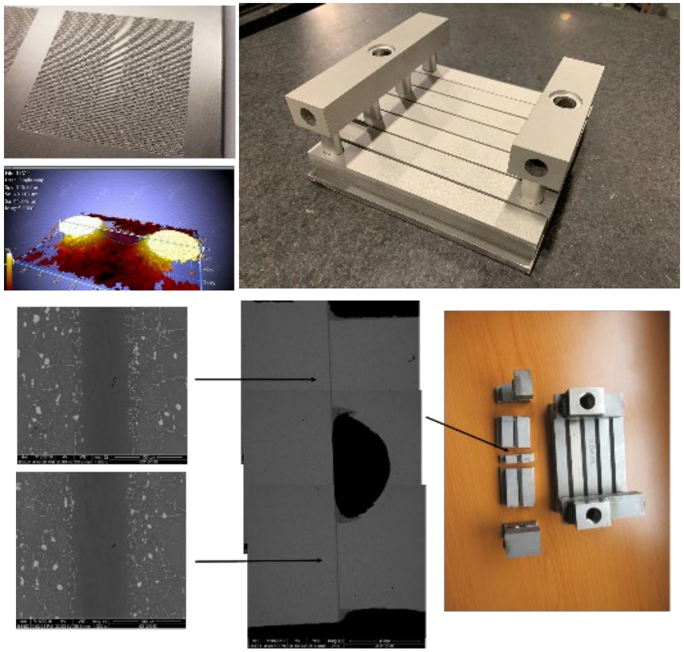


Fabrication Methods

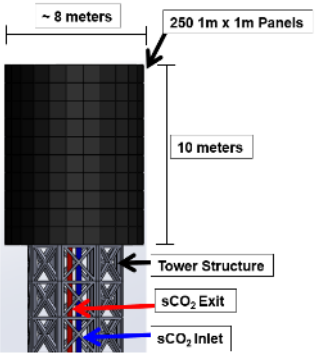
Thermal and Mechanical



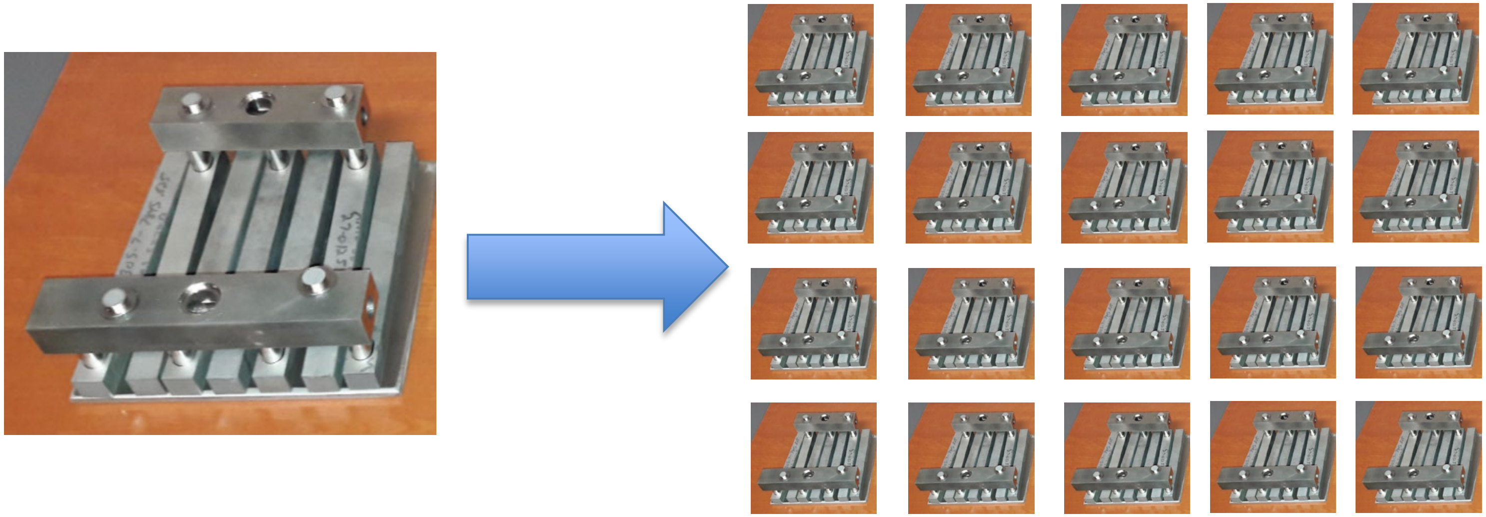
Mitigate Integrated Manufacturing Risks



Prototype Demonstration



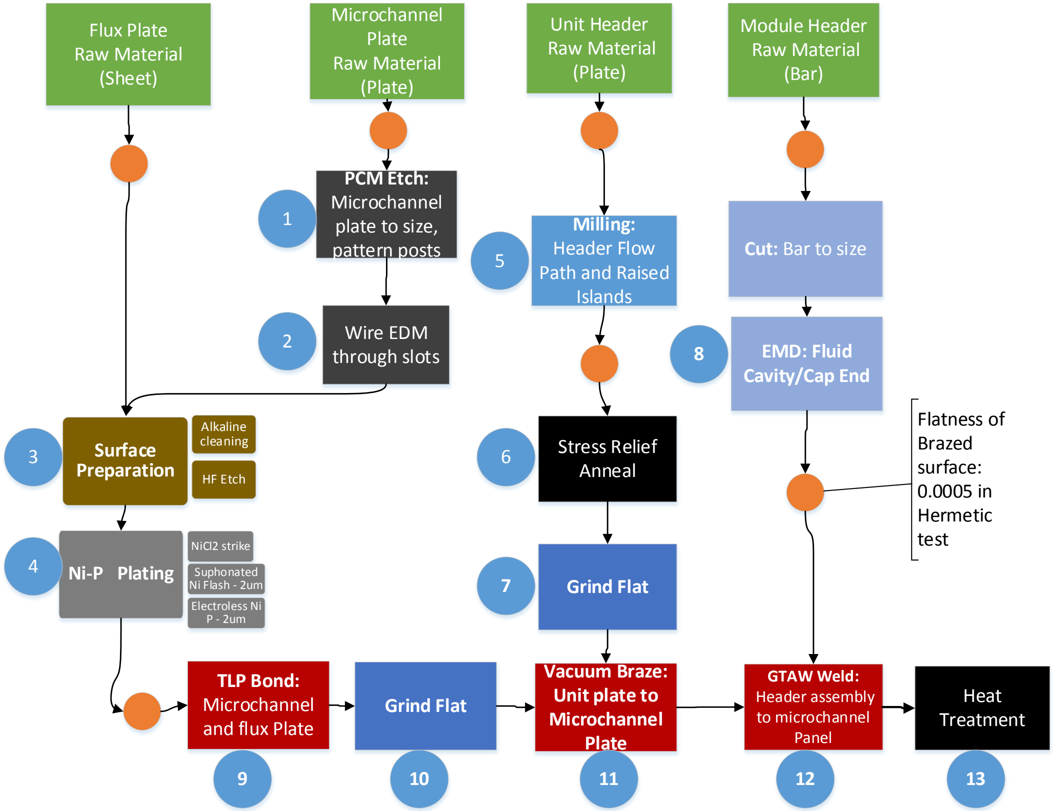
Manufacturing Risks



Potential Missed Risks

- Process limitations on design
- Availability of process capability
- Cost of demonstration/developing process
- Unexpected interactions between processes

Banking Innovation



Flux Plate Raw Material (Sheet)

Microchannel Plate Raw Material (Plate)

Unit Header Raw Material (Plate)

Module Header Raw Material (Bar)

1 **PCM Etch:** Microchannel plate to size, pattern posts

2 Wire EDM through slots

3 **Surface Preparation**
- Alkaline cleaning
- HF Etch

4 **Ni-P Plating**
- NiCl2 strike
- Suphonated Ni Flash - 2um
- Electroless Ni P - 2um

5 **Milling:** Header Flow Path and Raised Islands

6 Stress Relief Anneal

7 **Grind Flat**

Cut: Bar to size

8 **EMD: Fluid Cavity/Cap End**

Flatness of Brazed surface: 0.0005 in
Hermetic test

9 **TLP Bond:** Microchannel and flux Plate

10 **Grind Flat**

11 **Vacuum Braze: Unit plate to Microchannel Plate**

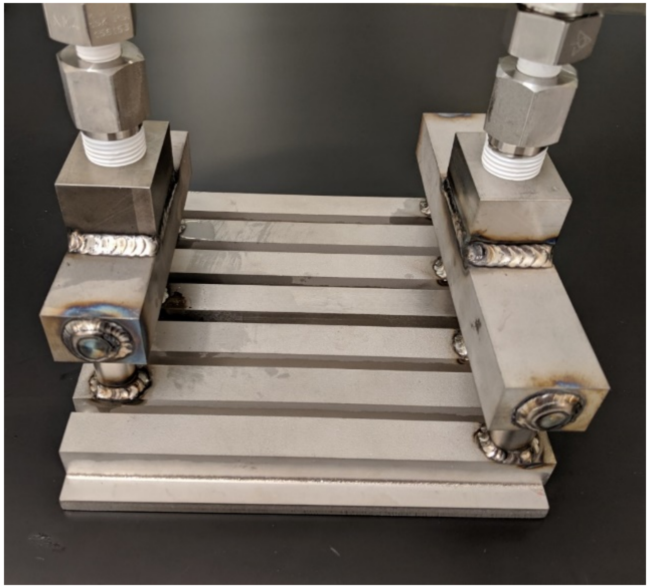
12 **GTAW Weld:** Header assembly to microchannel Panel

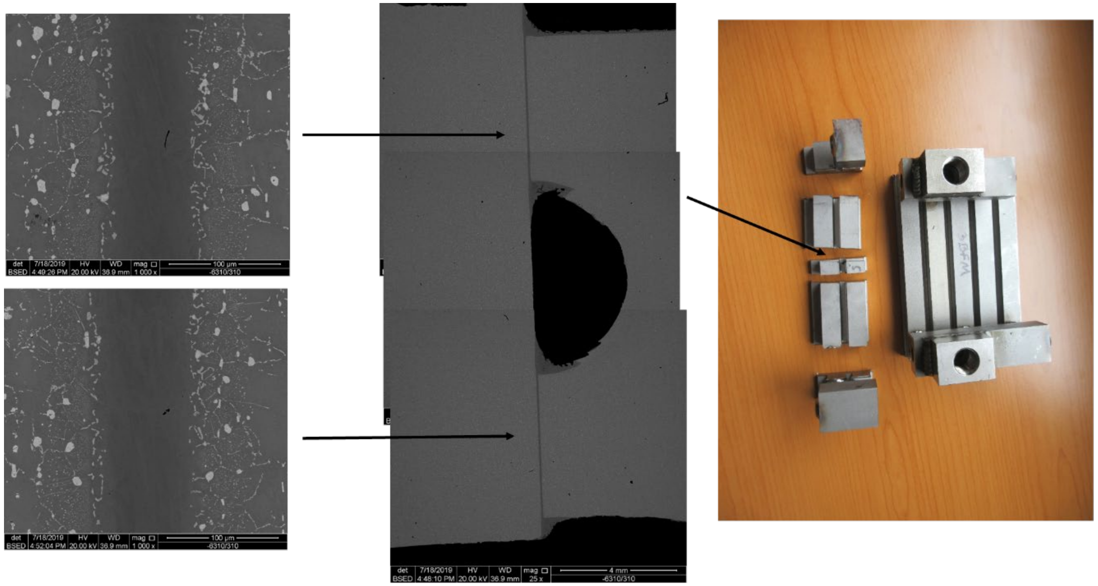
13 Heat Treatment

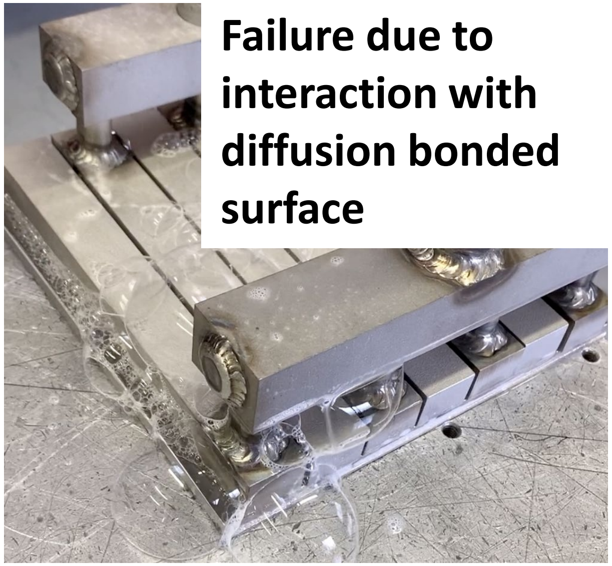
Ideal World:

- Develop manufacturing process
- Validate each step in processes
- Build multiple production prototypes

Example Approach - Challenges







Failure due to interaction with diffusion bonded surface

Brazing/Welding

- Headers-to-plate
- Proof test (pass)
- Destructive test(pass)

Manufacturing → 10 MWe

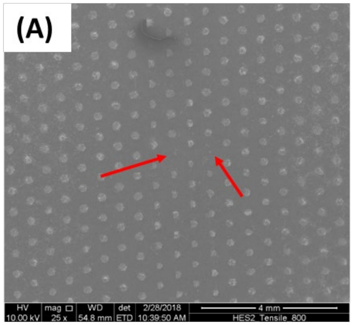
Ideal World:

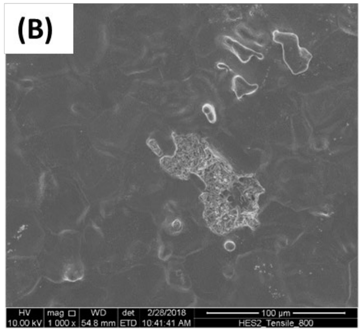
- Build multiple production prototypes
- Conduct reliability tests (e.g., temperature/pressure cycling)

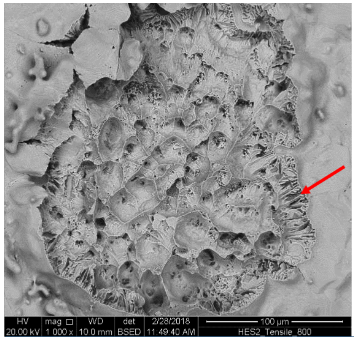
Potential R&D Challenges:

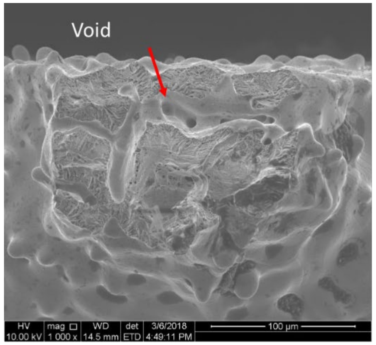
- Requires “final” design
- Expensive
- Time consuming
- Who is going to do it?
- Small volume in CSP → tool investment

Material/Mechanical Life Risks









Potential Missed Risks

- “Exotic” materials
- Limited experience (machining, forming, joining, etc.)
- Limited base material data at conditions
- Limited/no data on joints
- Extreme operation (difficult to replicate)
- Standards (ASME, UL) haven’t caught up

Banking Innovation → Materials/Mechanical

Potential R&D Challenges:

- Fund material data tests (similar to corrosion round robin in NE)
- Dedicated studies on joints and joint properties
- Develop centralized reliability testing capability (e.g., SNL)
- Develop industry informed CSP specific standards for receivers

Closing Thoughts

- Unexpected challenges from proof-of-concept to engineering prototype
- Manufacturing considerations should start day 1
- Coordinated effort on material properties
- Coordinated effort on joining technology and properties
- **Share failures and success**

Acknowledgments

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Vacuum Process Engineering

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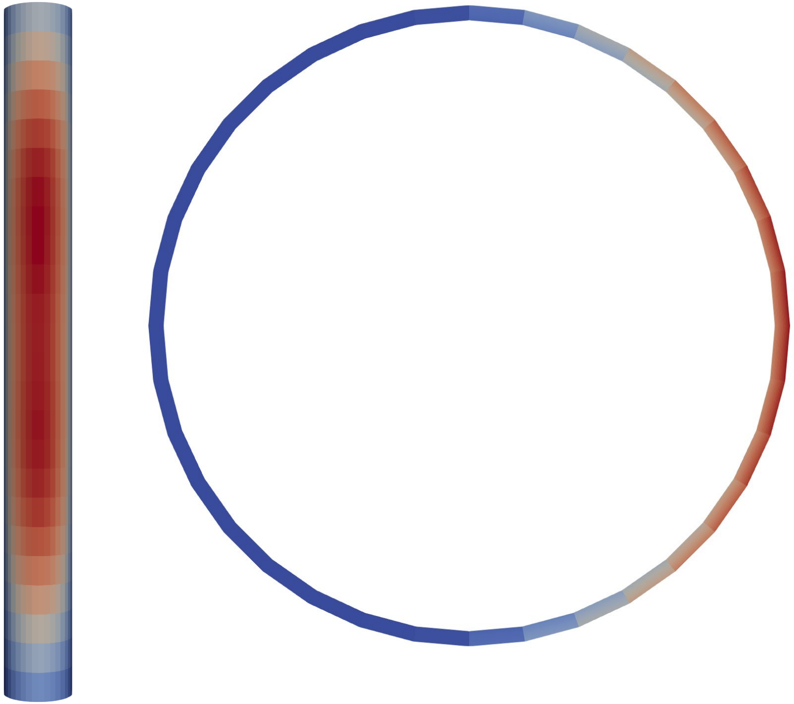
WE START WITH YES.

STRUCTURAL CHALLENGES FOR HIGH TEMPERATURE RECEIVERS

MARK MESSNER
Argonne National Laboratory

2020 Next Generation Receivers Workshop



QUICK OVERVIEW

Basic challenges

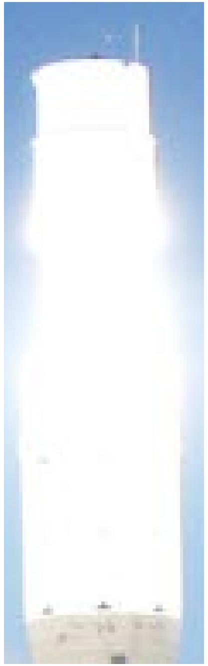
- Creep-fatigue
- Stress relaxation
- Metal thermal properties

Key structural factors

- Everything fails eventually
- Thicker is not better
- Circumferential versus axial thermal gradients
- Strength decrease in γ/γ' Ni-based alloys

Potential solutions

- Lower inlet/outlet temperature
- Solar aiming, reflectors, cavities
- Structural health monitoring (digital twin)
- New materials (ceramics, cermets, HEAs)



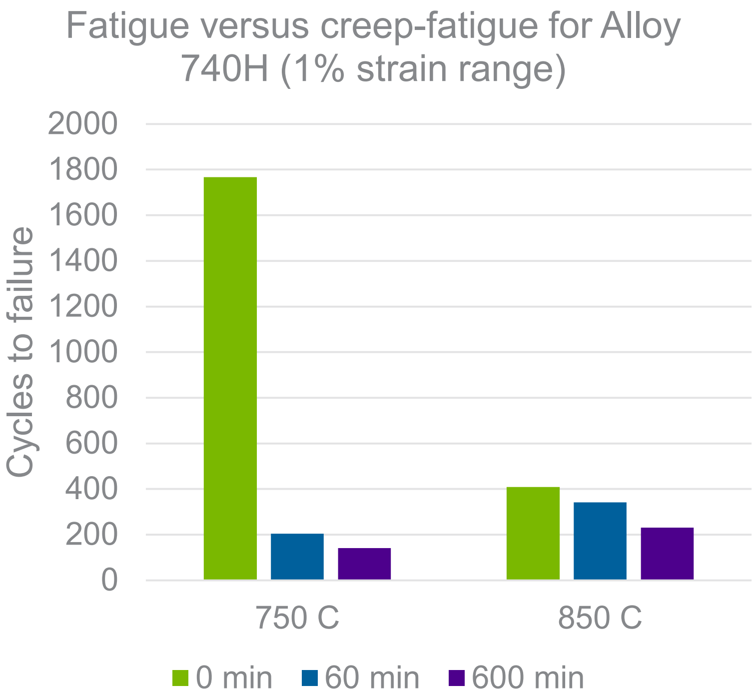
NREL/TP-5500-57625

Caveats: focus here on structural damage (versus environmental) and on tubular receiver designs

Many of these lessons-learned apply to other types of designs, but coolant compatibility is a key factor in selecting a receiver material

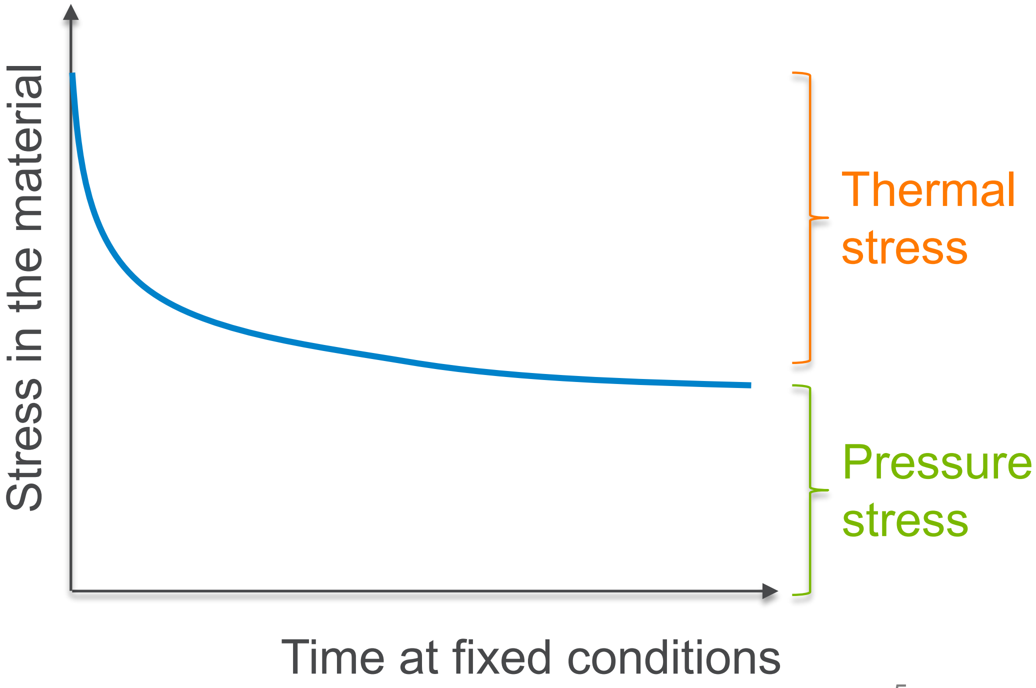
BASIC CHALLENGES

CREEP-FATIGUE IS THE DOMINANT FAILURE MECHANISM FOR HIGH TEMPERATURE RECEIVERS



- At high temperatures the combination of creep and fatigue is much more damaging than each individually:
  - Fatigue: failure under cyclic load
  - Creep: failure under steady load
  - Creep-fatigue: combination of cyclic load + holds at steady conditions
- ***Designing to the fatigue diagram can underpredict life by an order of magnitude***

CREEP AND STRESS RELAXATION OCCUR AT HIGH TEMPERATURES, REQUIRING TIME-DEPENDENT ANALYSIS



- Material deforms over time even at fixed load (creep deformation)
- Structural analysis must be transient/time-dependent (or at least account for creep)
- Creep relaxes high stresses – both a material and a structural effect
- We worry about two “types” of stresses:
  - Stress from pressure: can’t be relaxed
  - Thermal stress: can relax away with time
- Creep deformation can be a good thing if you believe damage ~ stress!

METAL AND WORKING FLUID THERMAL PROPERTIES CONTROL THE MAGNITUDE OF THE THERMAL STRESS FOR FIXED FLUX

Increasing the following does what to the thermal stress?

Increases thermal stress

- Thermal expansion coefficient
- Thickness
- Elastic stiffness

Decreases thermal stress

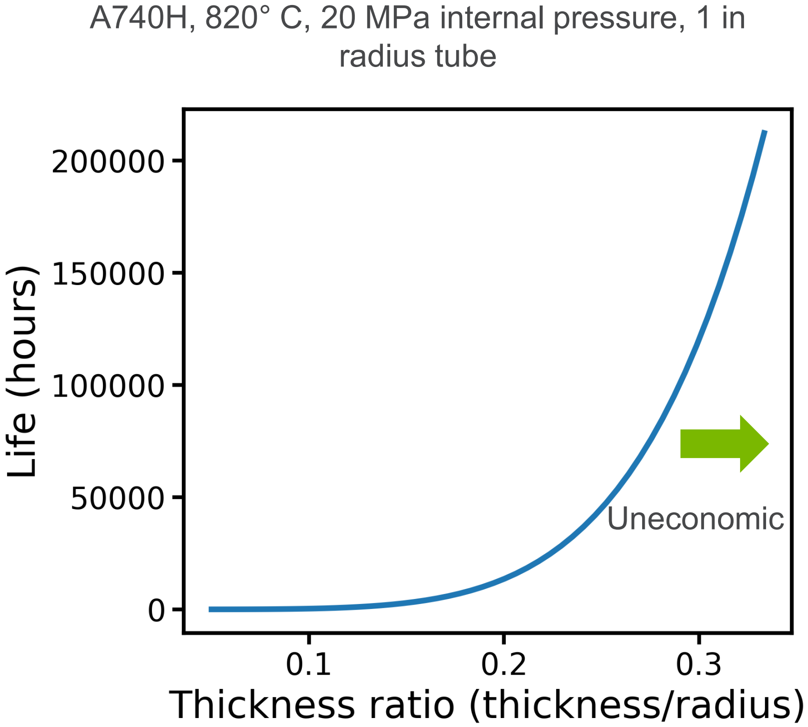
- Thermal conductivity

Increasing convection with the fluid decreases the maximum metal temperature

KEY OBSERVATIONS ON STRUCTURAL DESIGN

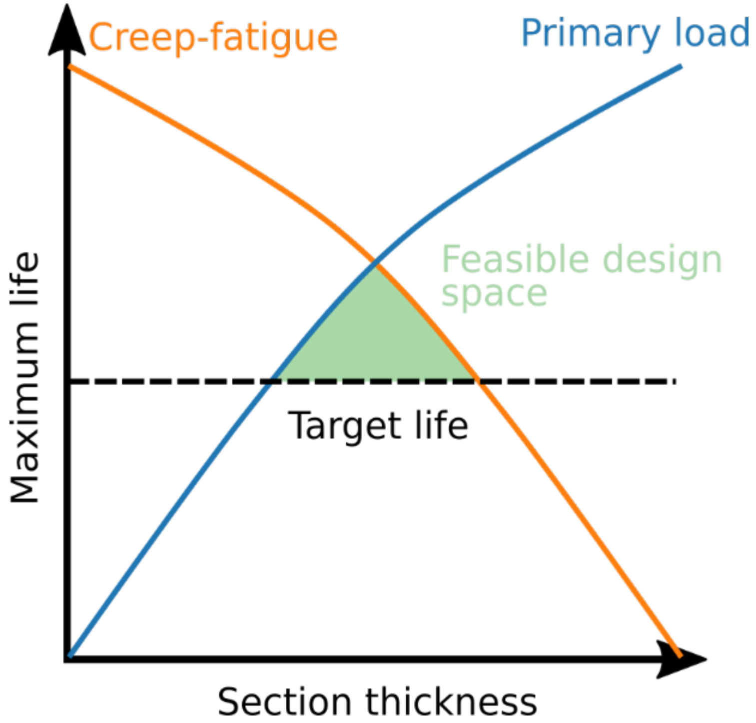
EVERYTHING FAILS EVENTUALLY

Key difference from low temperature design



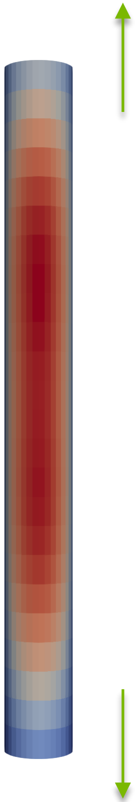
- Low temperature design: structure designed to withstand the load
- High temperature design: structure designed to resist the load for a certain period of time
- Example: creep life at fixed temperature
- Subtle point about Section I/VIII ASME design: typically assume 100,000 hour properties but do not explicitly consider a design life

THICKER IS NOT BETTER

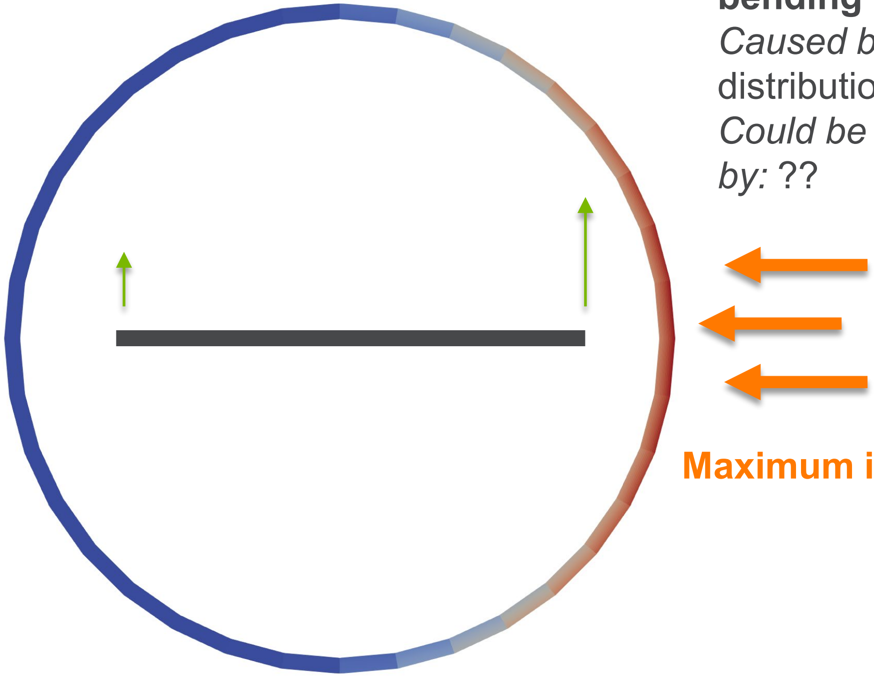


- Unlike low temperature design based on pressure only you can’t design your way out by increasing the section thickness
- **Two competing design limits:**
  - *Pressure*: **increasing** thickness improves creep rupture/plastic collapse
  - *Thermal stress:* **decreasing** thickness improves fatigue/creep-fatigue

CIRCUMFERENTIAL THERMAL GRADIENTS ARE WORSE THAN NET THERMAL EXPANSION



Net axial expansion
Caused by: net tube temperature increase
Could be alleviated by: bellows



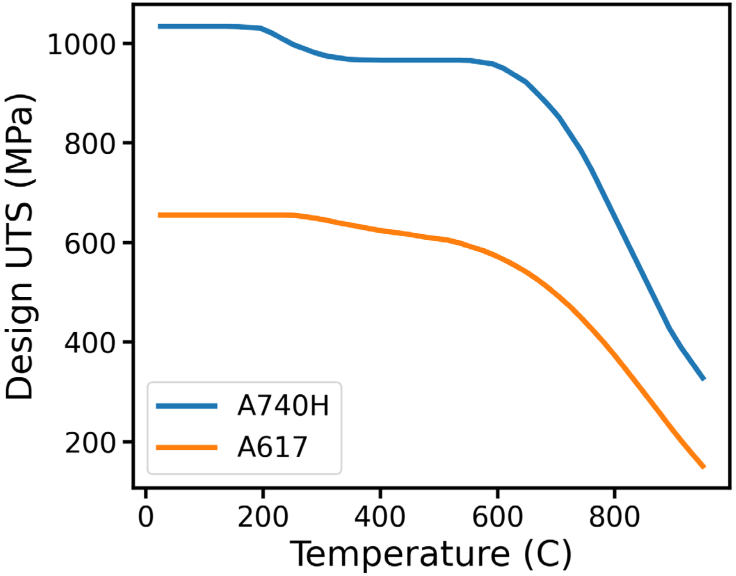
Circumferential bending
Caused by: flux distribution
Could be alleviated by: ??

Maximum incident flux

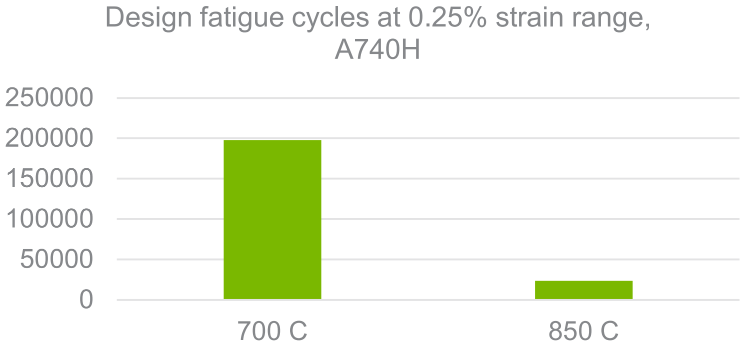
In our experience circumferential bending is much more challenging than net tube expansion

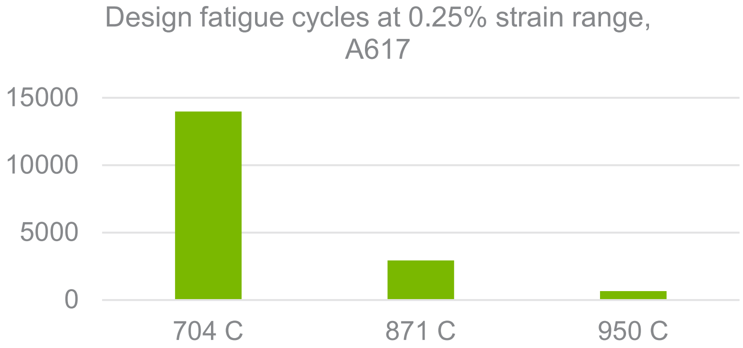
THE STRENGTH OF NI-BASED ALLOYS DROPS OFF PAST ~ 775℃

Shift in precipitation kinetics significantly reduces γ' phase nucleation and growth



Change associated with shift from work hardening to perfectly-plastic behavior



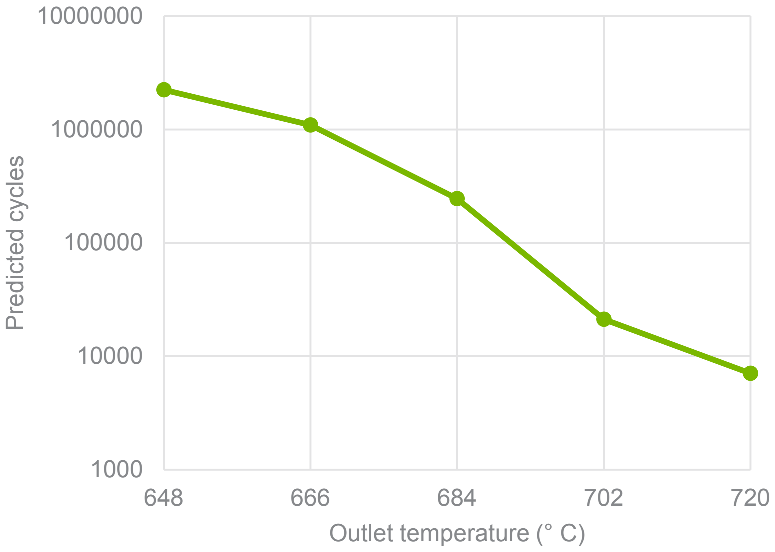


POTENTIAL SOLUTIONS

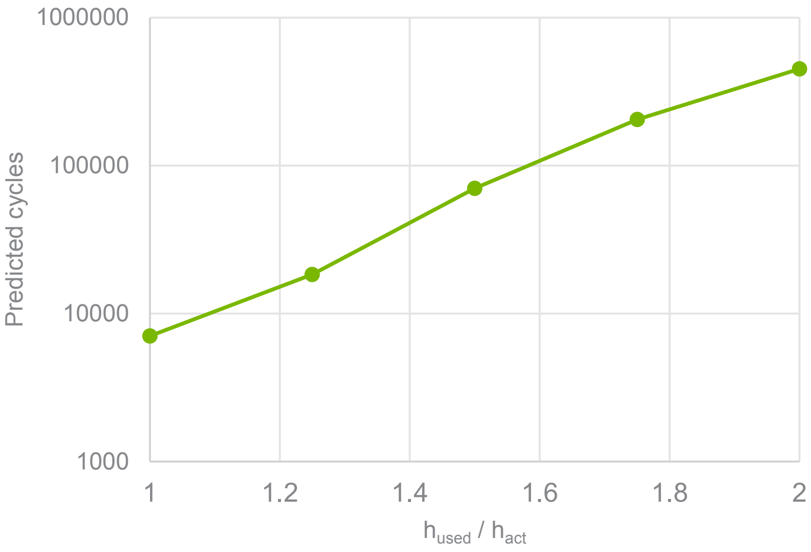
ACCEPT A LOWER OUTLET TEMPERATURE OR USE A “BETTER” WORKING FLUID

Not an ideal solution, but certainly feasible

Reference A740H salt receiver as a function of outlet temperature (fixed flux, 1D analysis)

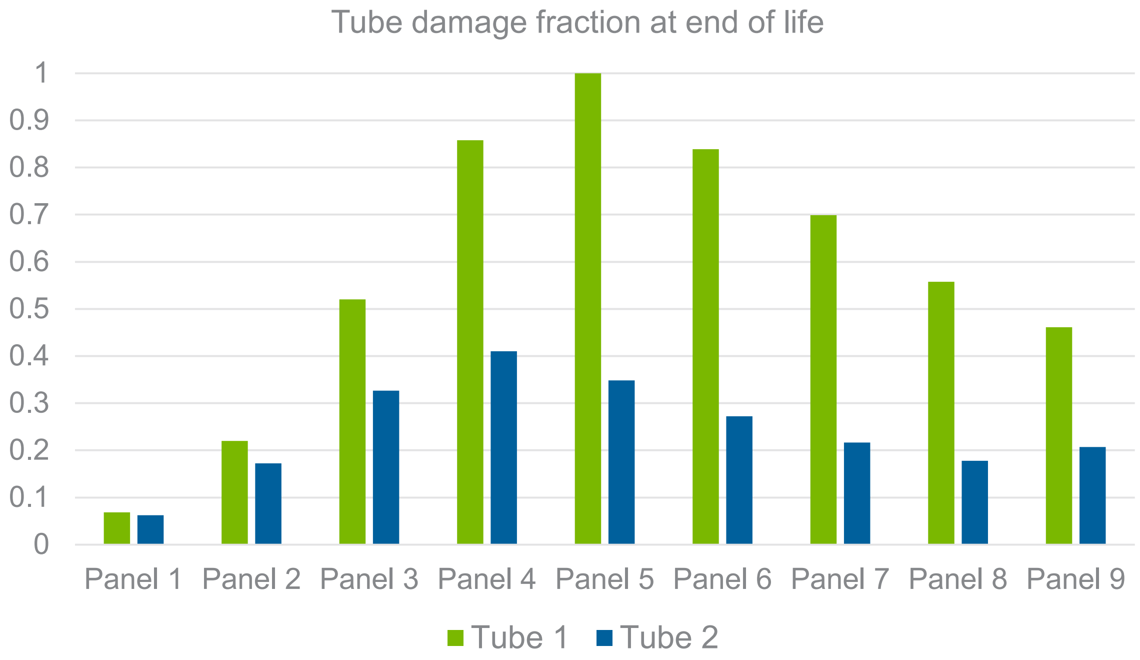


Reference A740H salt receiver as a function of working fluid convective heat transfer coefficient (fixed flux, 1D analysis)



DISTRIBUTE THE DAMAGE MORE UNIFORMLY

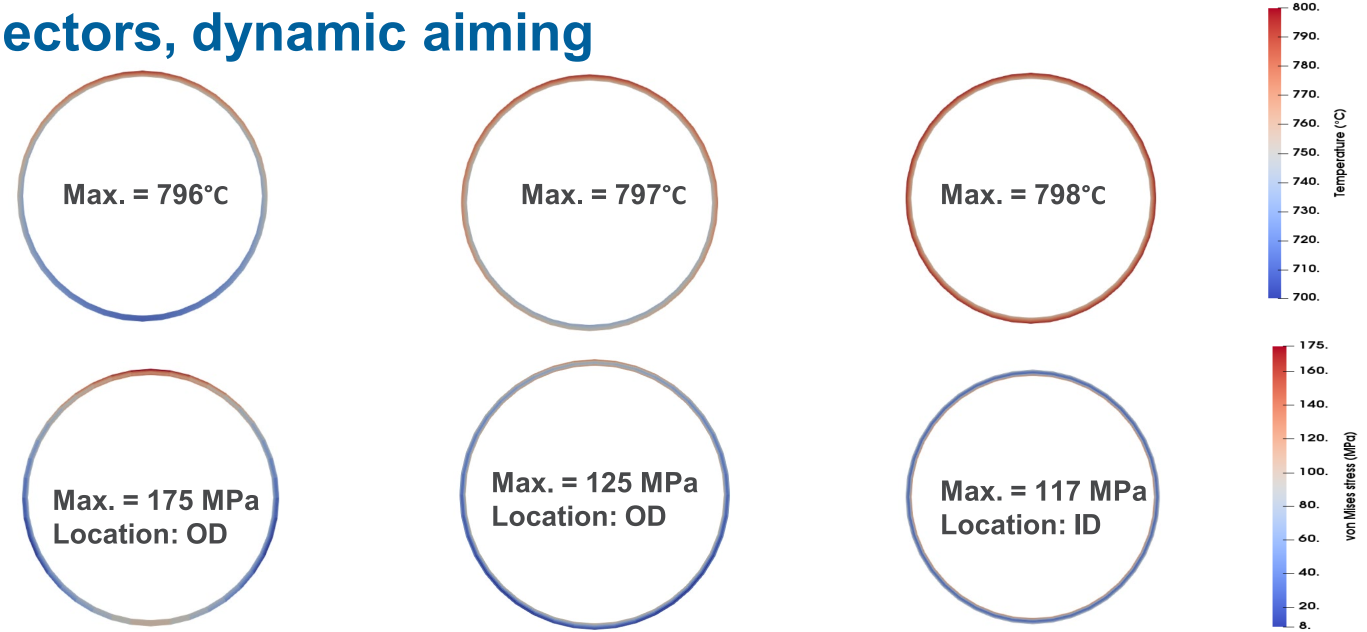
Repair and replace tubes, structural health monitoring



- Peak damage occurs only in a limited number of tubes in the receiver
- Remaining tubes have substantial residual life
- Take advantage of that:
  - Monitor development of damage in tubes
  - Repair/replace when required
- Design changes to accommodate this strategy?
- In situ health monitoring (digital twin)?

DISTRIBUTE THE FLUX MORE UNIFORMLY

Cavities, reflectors, dynamic aiming



Temperature

Max. = 796°C

Max. = 797°C

Max. = 798°C

Von Mises stress

Max. = 175 MPa
Location: OD

Max. = 125 MPa
Location: OD

Max. = 117 MPa
Location: ID

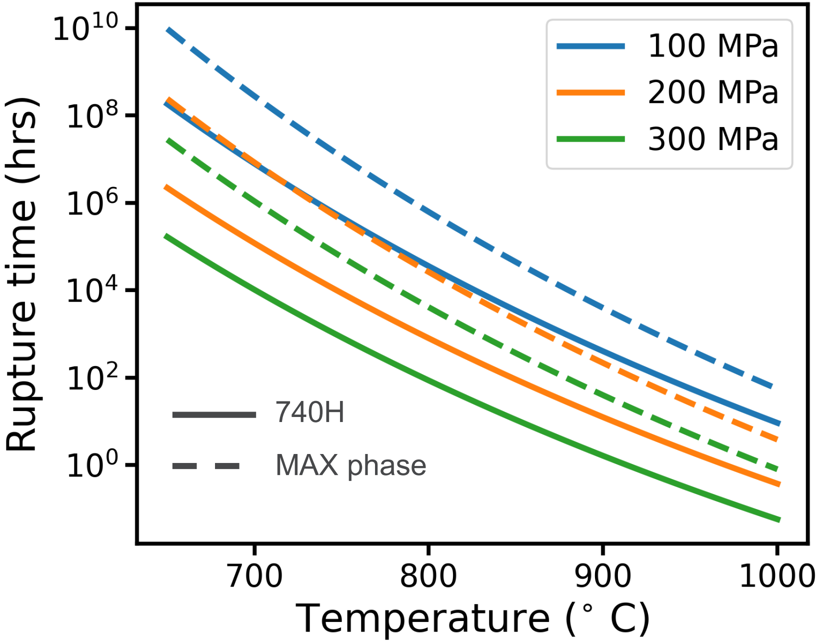
Case:1
- *Maximum circumferential flux variation (e.g. a typical external receiver)*
- *Creep-fatigue life = 61 days*

Case:2
- *Reduced circumferential flux variation (e.g. a cavity receiver, an external receiver with reflectors at the back of the tubes)*
- *Creep-fatigue life = 377 days*

Case:3
- *No circumferential flux variation (e.g. an ideal cavity receiver)*
- *Creep-fatigue life = 4877 days*

USE NEW MATERIALS WITH BETTER CREEP/CREEP-FATIGUE RESISTANCE AT TEMPERATURE

- Ceramic based-materials maintain creep strength to much high temperatures, when compared to Ni-based superalloys
  - Creep strength fairly well established (albeit at higher temperatures)
  - *Creep-fatigue (or fatigue) strength less studied*
- There are other candidate metallic material systems:
  - HEAs
  - ODS alloys
  - Co superalloys
- Substantial practical challenges:
  - Forming (AM?)
  - Joining
  - Thermal properties (for *some* ceramics)
- Additional challenge: design practices for non-ductile materials



Projected creep-rupture comparison between Ni-based Alloy 740H and MAX phase material

Receiver Operations and Solar Field Integration

Impactful R&D for Technology Adoption

Mike Wagner, PhD, University of Wisconsin-Madison

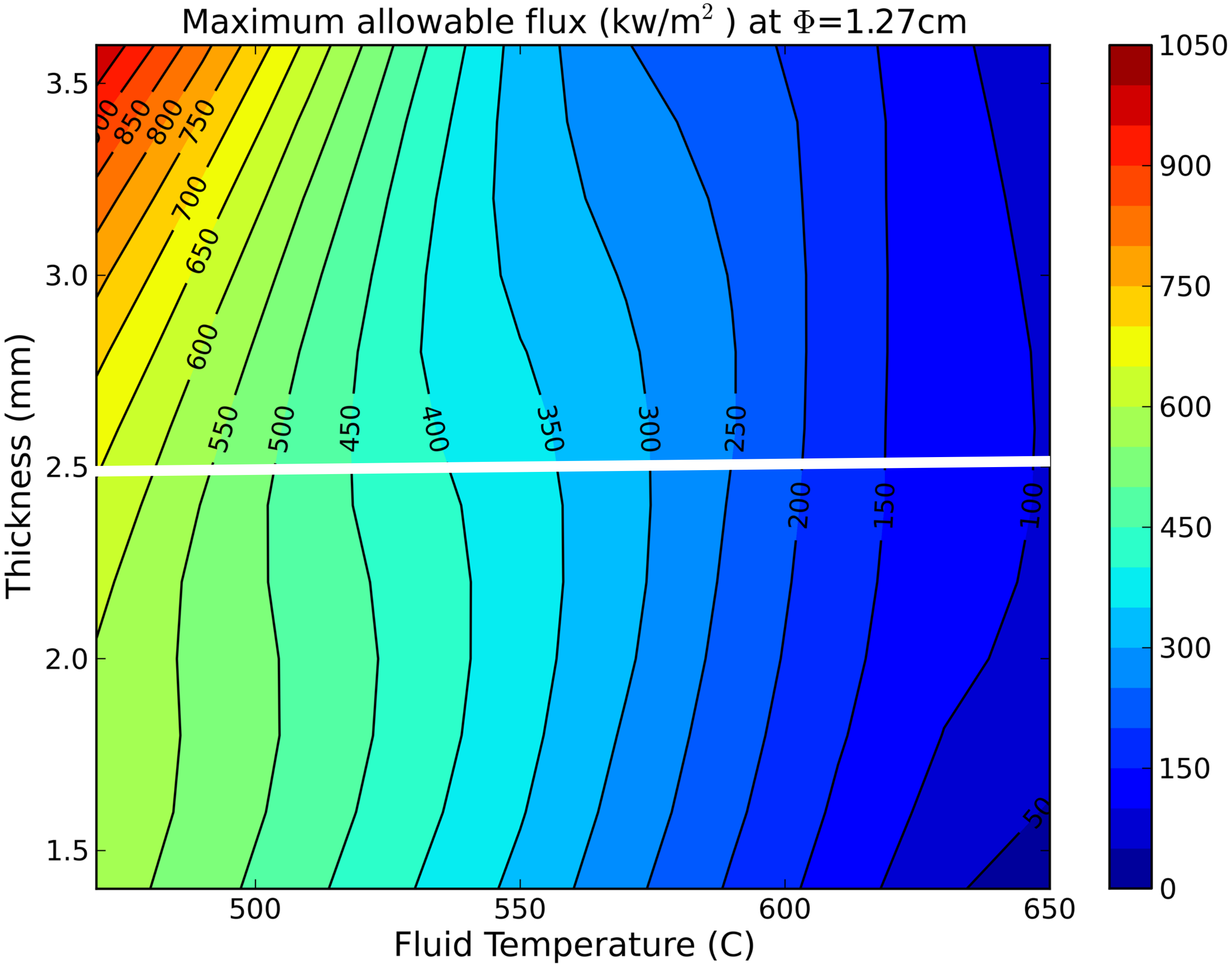
Contributors: T. Neises, J. Martinek, W. Hamilton (NREL), M. Kirschmeier, S. Sullivan (Brayton)

Topics

1. The role of allowable flux in receiver design
2. Heliostat optics and desired flux profiles
3. Influence of spillage loss on receiver design
4. Impact of non-ideal receiver flow control
5. Considering multiple receiver targets

Allowable flux drives receiver design

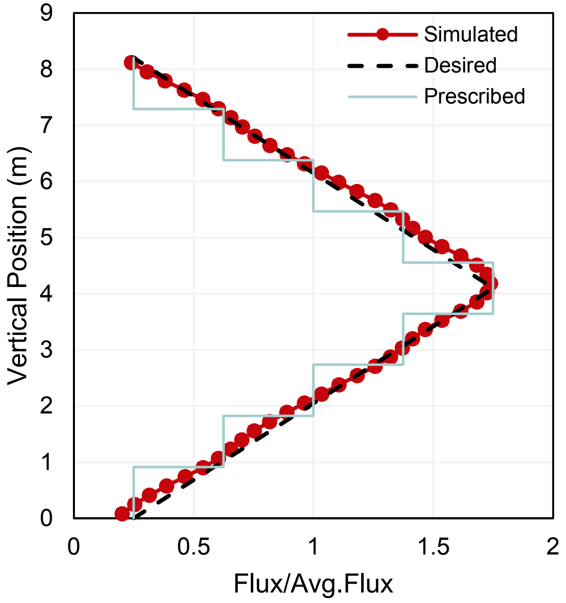
- Allowable flux in a fluid-based receiver (gas, liquid) depends on temperature & pressure
- Design decisions can include tube thickness, for example
- Allowable flux is generally higher for thick-walled tubes of a given diameter due to improved stress resistance, but sacrifices pressure drop
- Reproducing allowable flux limit profile *exactly* during operation maximizes thermal efficiency

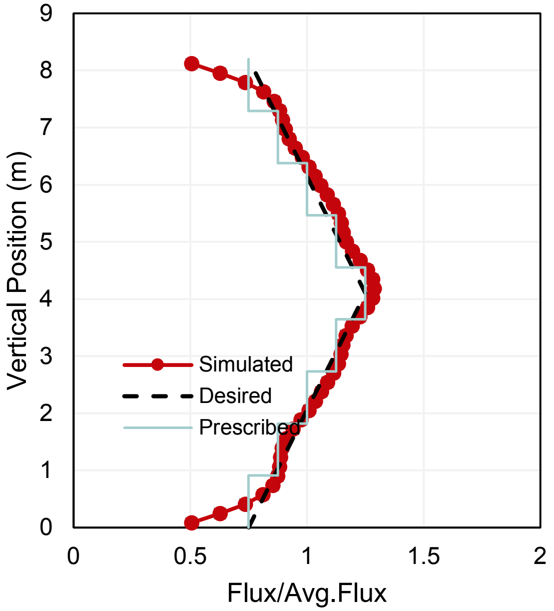


Not all ideal flux profiles can be realized

- Consider "triangular" ideal flux profile with max at receiver vertical centerline:
  - Spillage loss can be reduced by shifting heliostat images at edge toward the center
  - Ideal flux is not met near edge of receiver
  - Mass flow set to maintain max local material temperature
  - Temperature at outlet does not meet target!

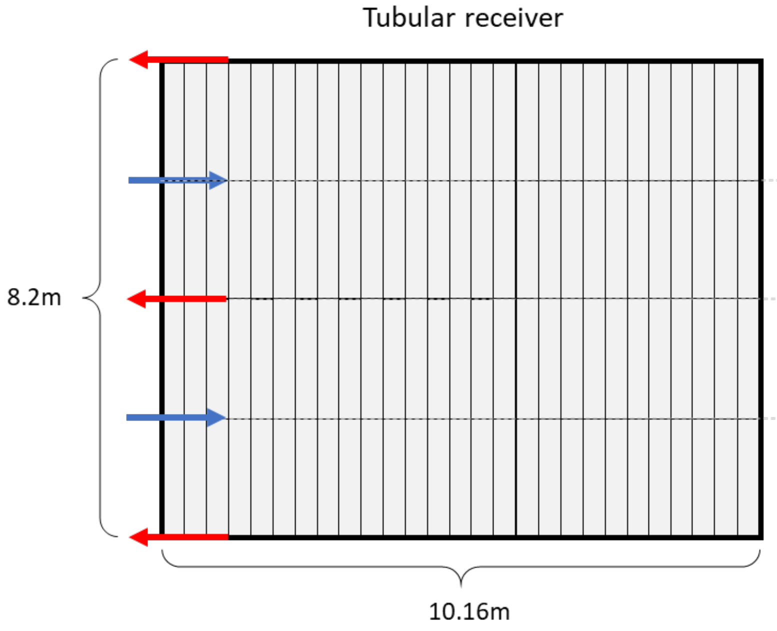
- Receiver size can be increased to maintain desired profile shape
  - Less efficient / more expensive

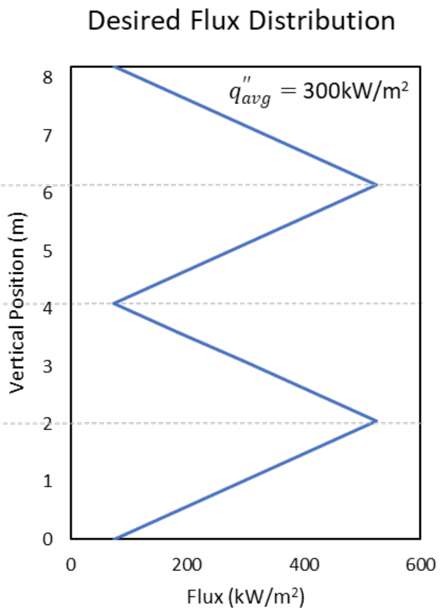


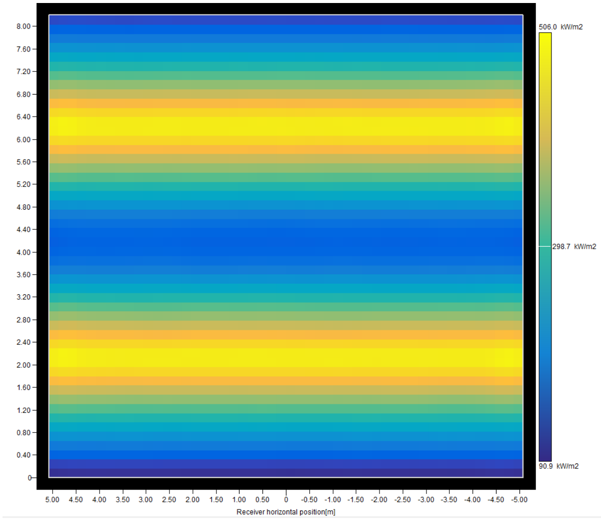


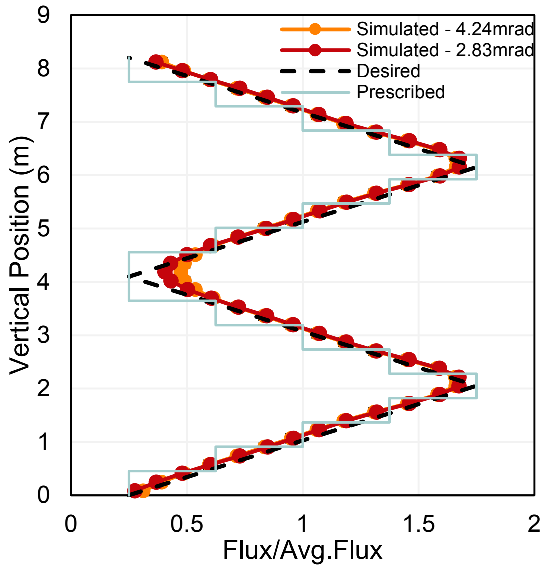
More complex profiles may violate local flux limit

- How does simulated flux profile vary with the *complexity* of the desired flux profile?
- Dependent on:
  - Heliostat characteristics
  - Field size vs size of geometry features



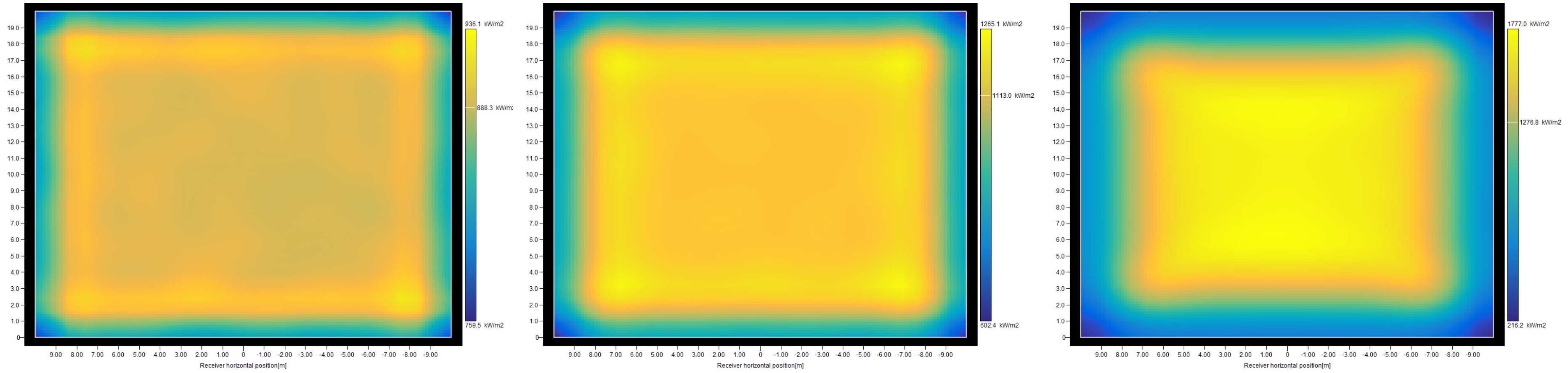


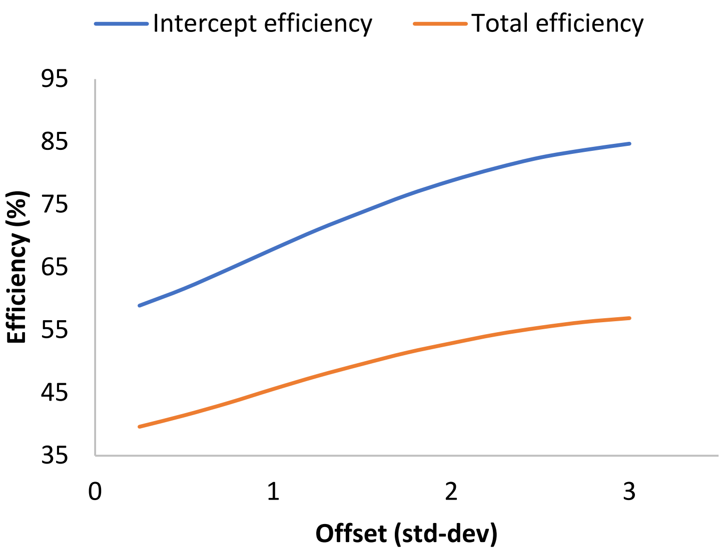


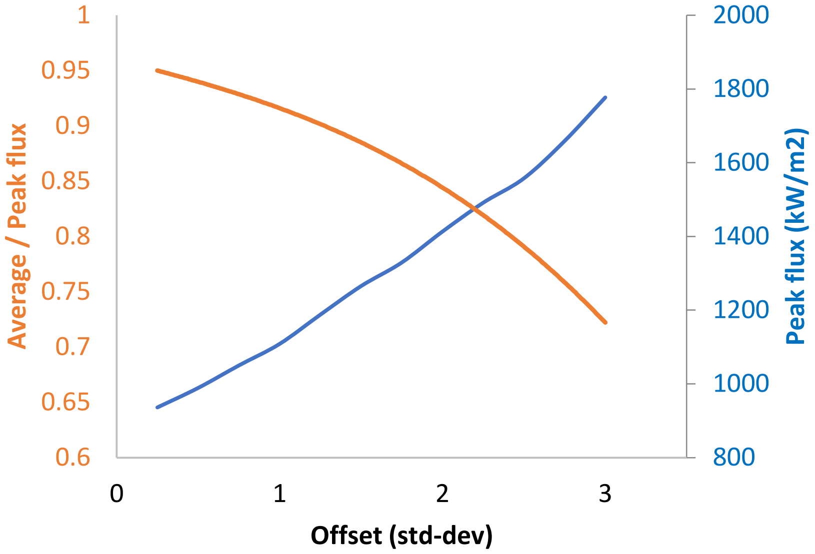


Field efficiency and flux “quality” compete

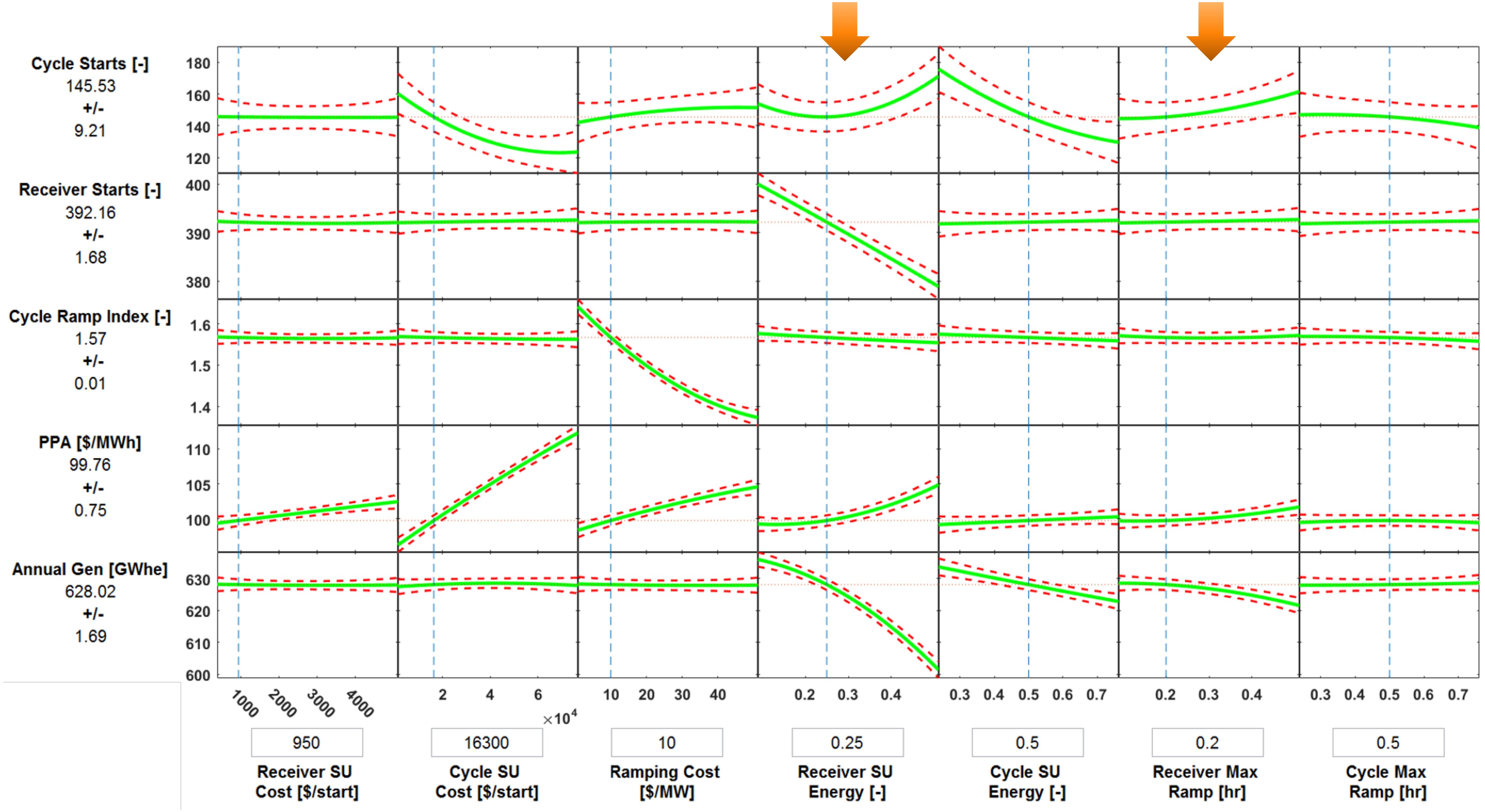
Increasing offset of images from receiver edge →







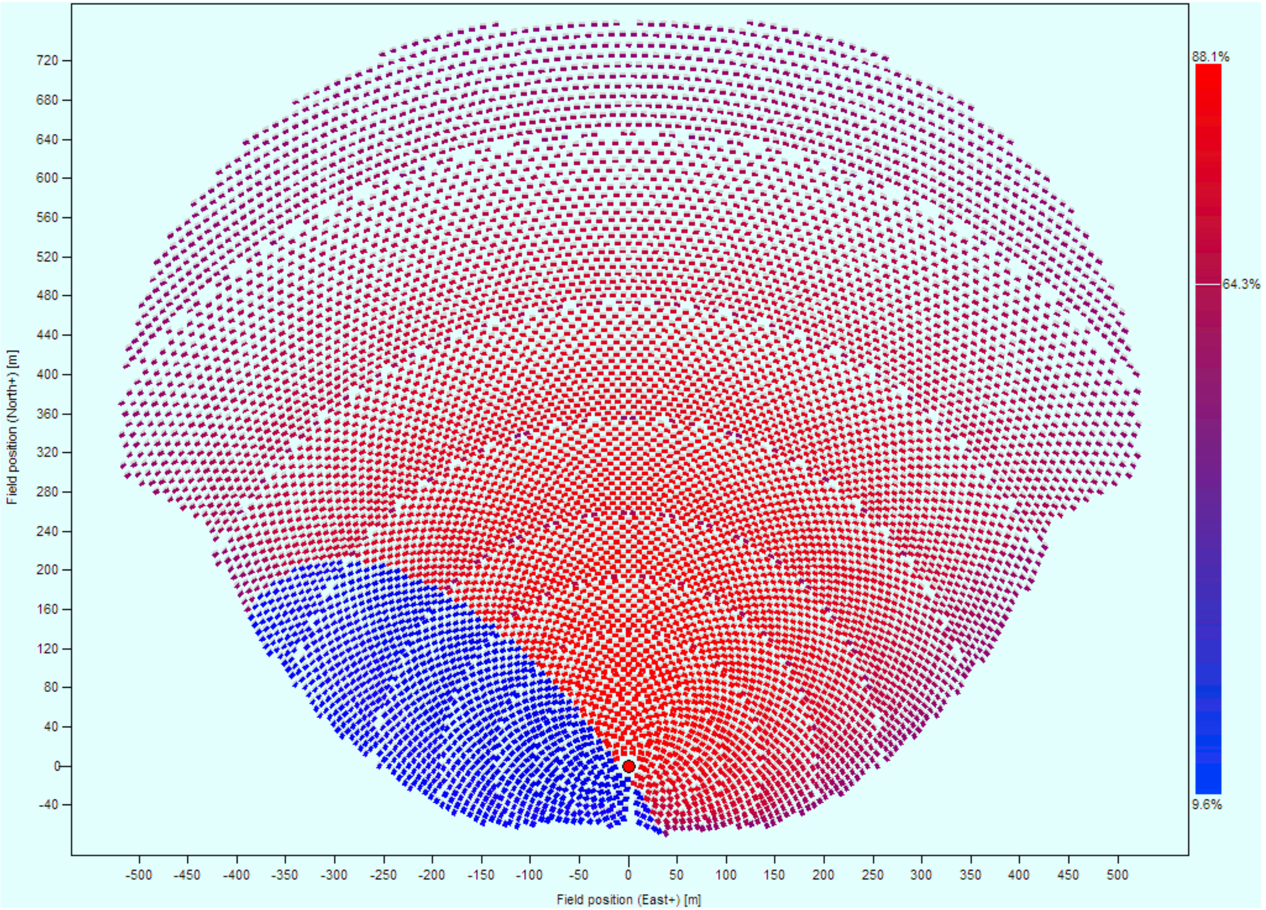
What is the impact of receiver startup?



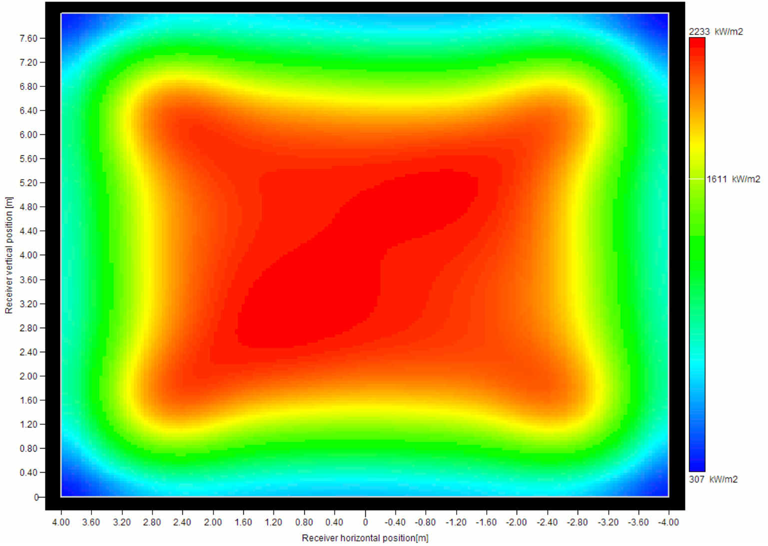
Consider possible operation during transients

- Do operational considerations impact receiver design?
- How quickly might conditions change during operation?
- Can the receiver operate through flux transients?

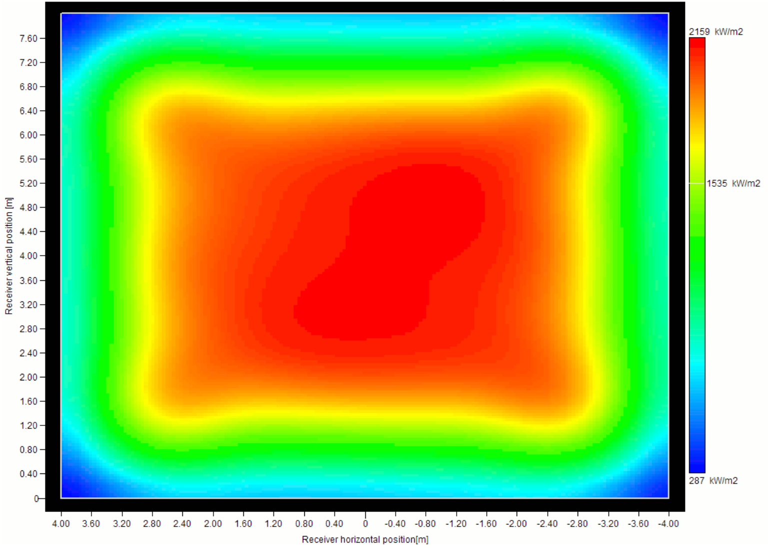
Receiver Transient Operation



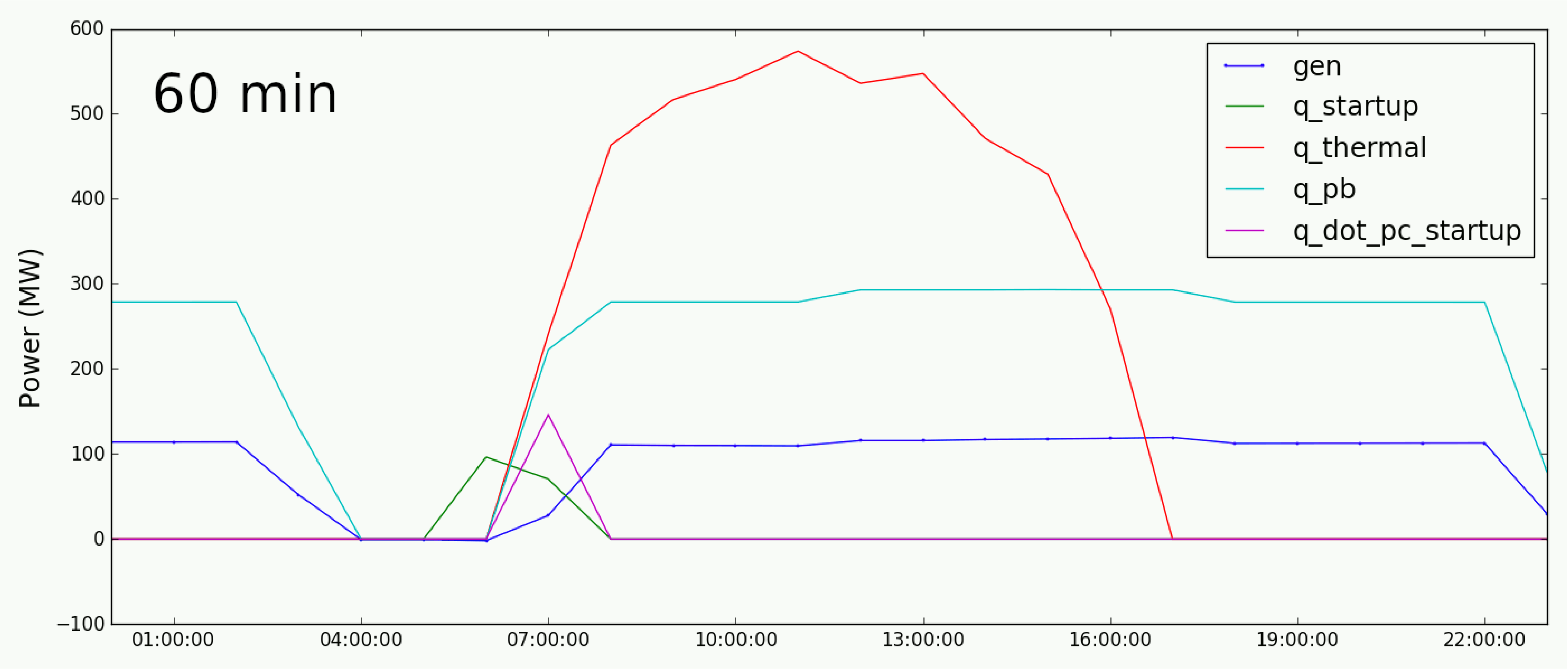
Static aiming



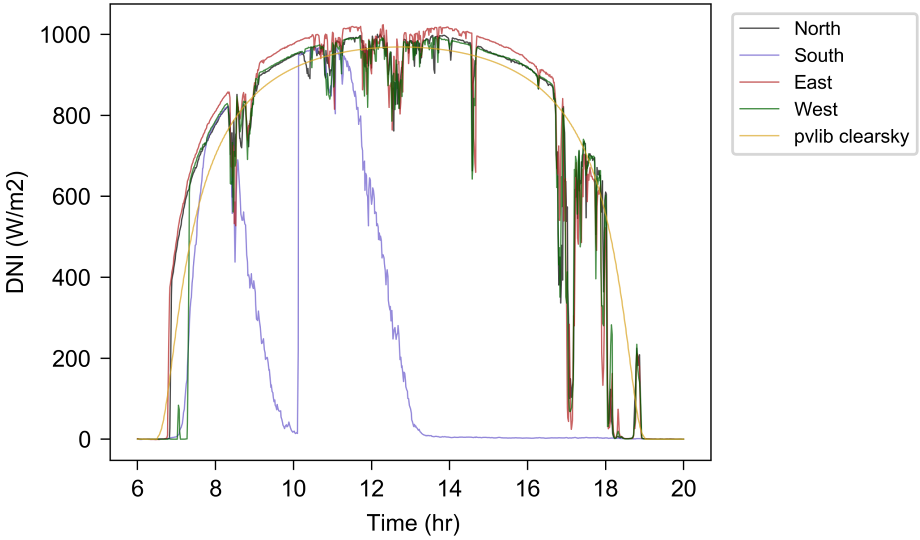
Dynamic aiming

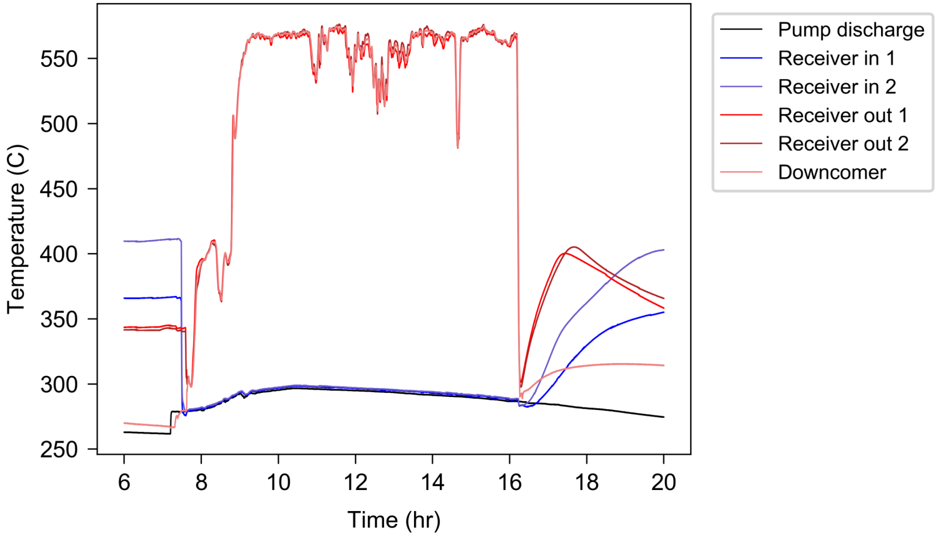


Data resolution is important to identifying possible operating scenarios

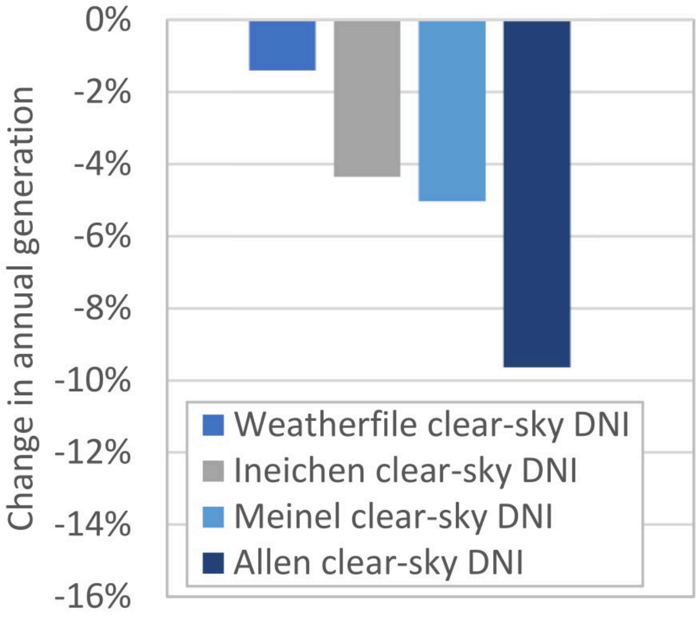


Ideal mass flow control risks receiver burnout



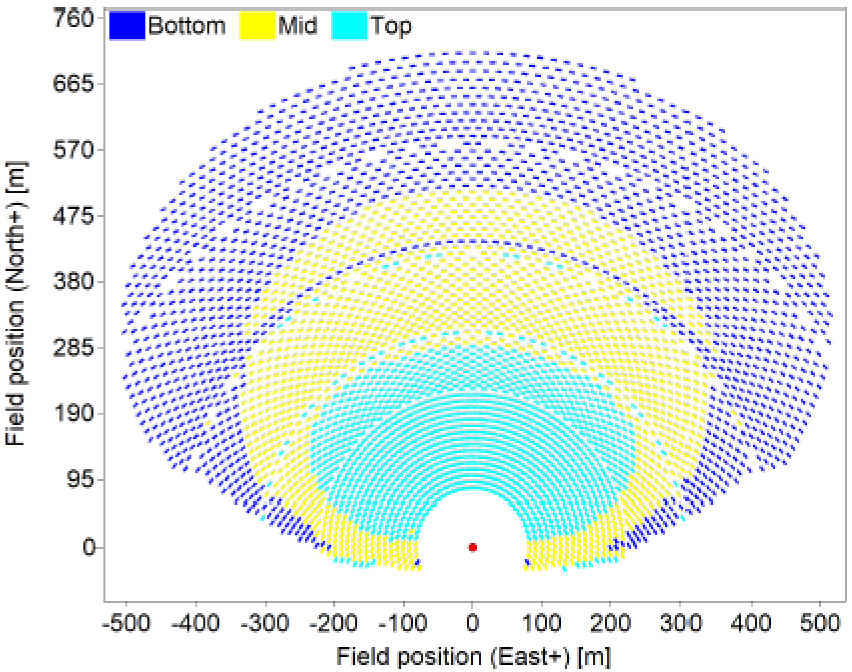


- Control based on clear sky DNI is safest
- Inaccurate models significantly reduce long-term performance
- More work on improved flow / temperature control is needed



Flux control for receivers with multiple targets

- Consider north-only field with top, middle, bottom targets of equal size
- Heliostats are optimally assigned based on optical performance
- We manually reassign optimal target using a randomized factor



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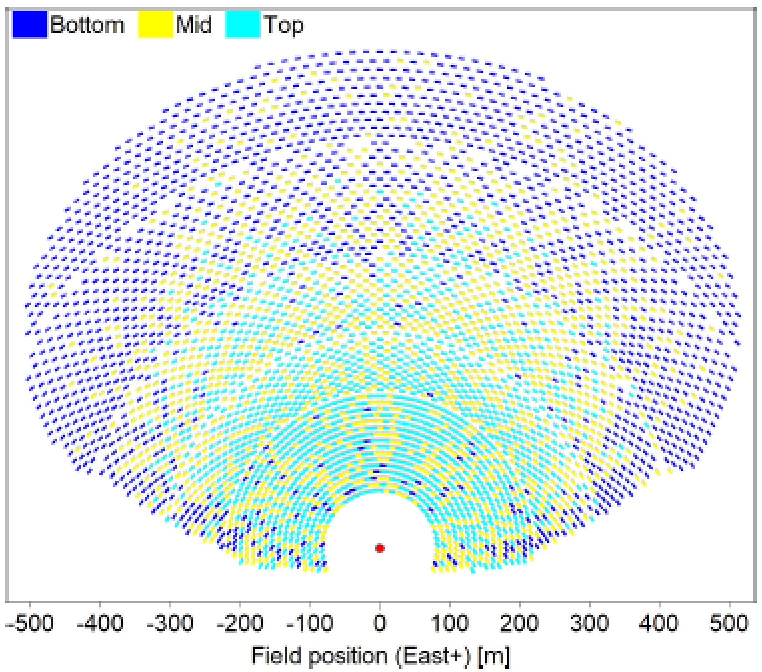

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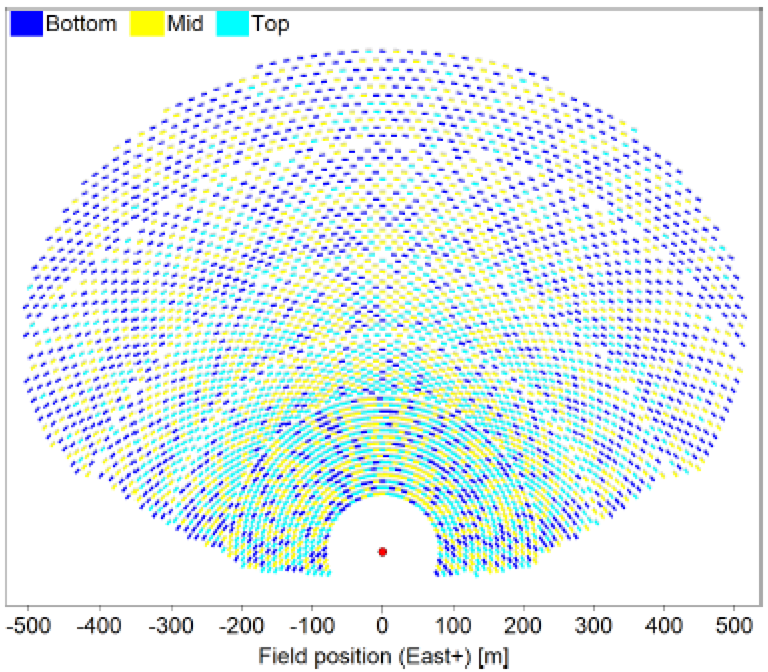

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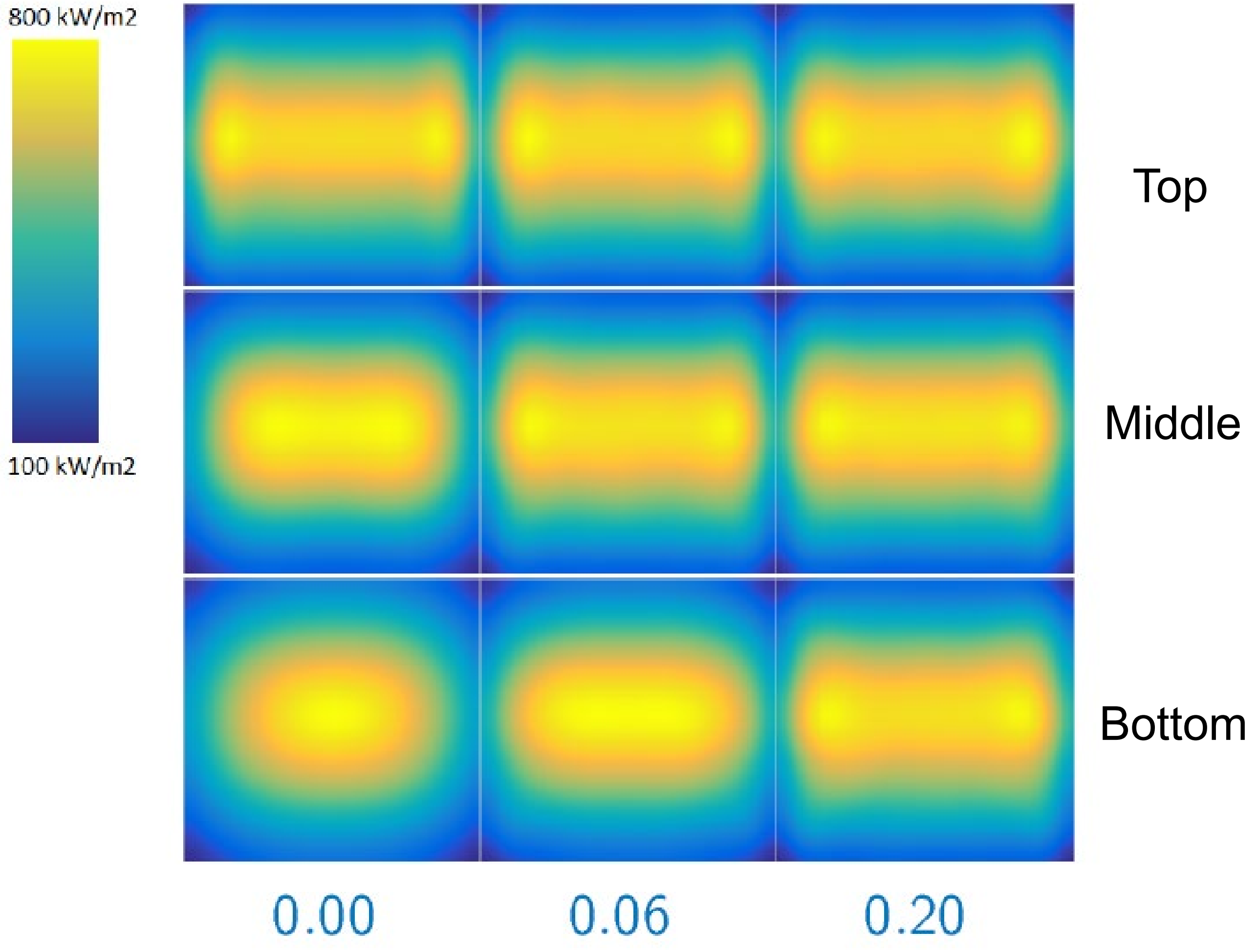
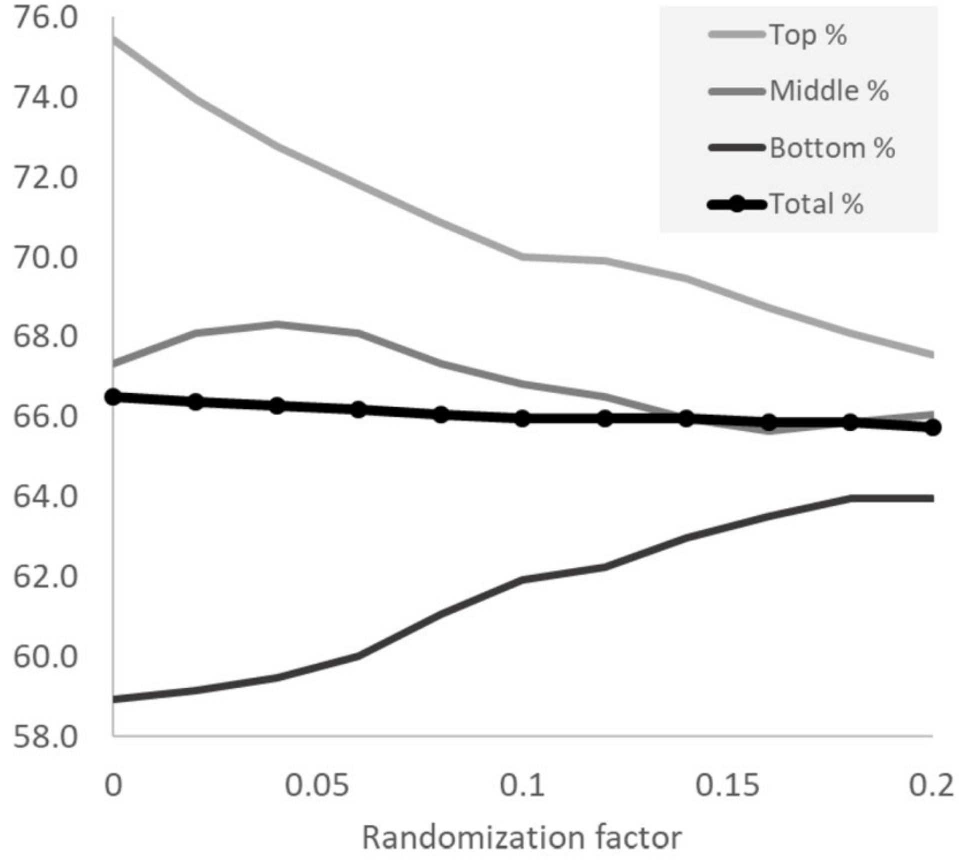
Multiple targets balance flux uniformity with overall field efficiency


Flux by receiver target for 3 randomization factors


Optical efficiency by target

Summary

- Allowable flux is local, depends on fluid conditions, and determines optical requirements from the field
- Heliostat field modeling can help determine ideal flux profile feasibility and should be considered in preliminary work
- The most optically efficient heliostat field may not produce a feasible flux profile
- There is a need for standardized optical characterization and acceptance of heliostats
- Receiver startup, shutdown, and ramping limits can have a large impact on productivity
- Design is not complete until off-design is considered
- Hourly irradiance data does not capture full receiver boundary condition variability
- Consider methods for and impact of controlling mass flow under variable irradiance

Thank you!

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NE NOOTER/ERIKSEN
HEAT RECOVERY STEAM GENERATORS

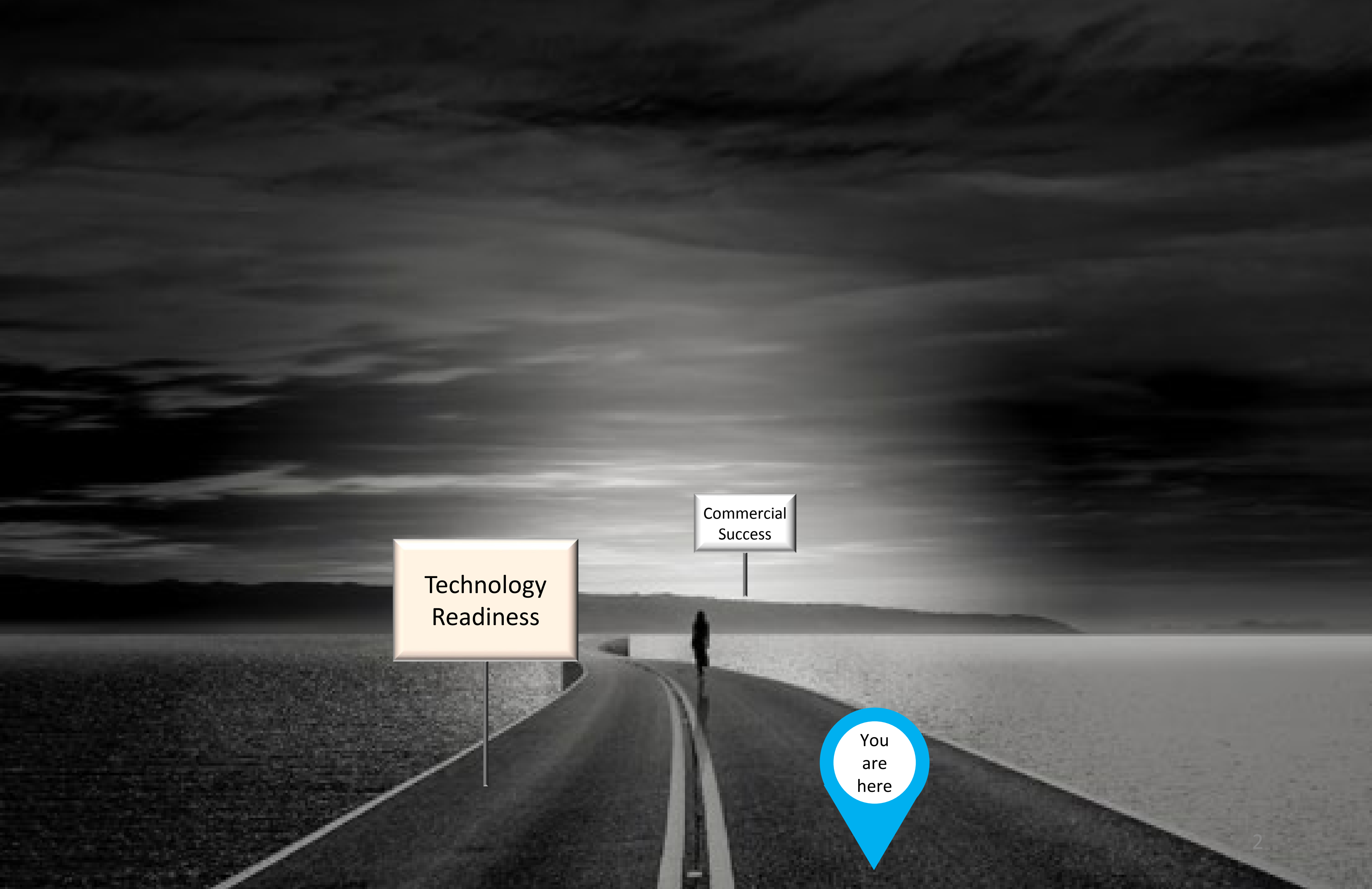
Impactful R&D for Technology Adoption

SETO CSP Virtual Workshop on Next Generation Receivers

29 October 2020

David Wait, Nooter/Eriksen

How to travel the path to commercial success?

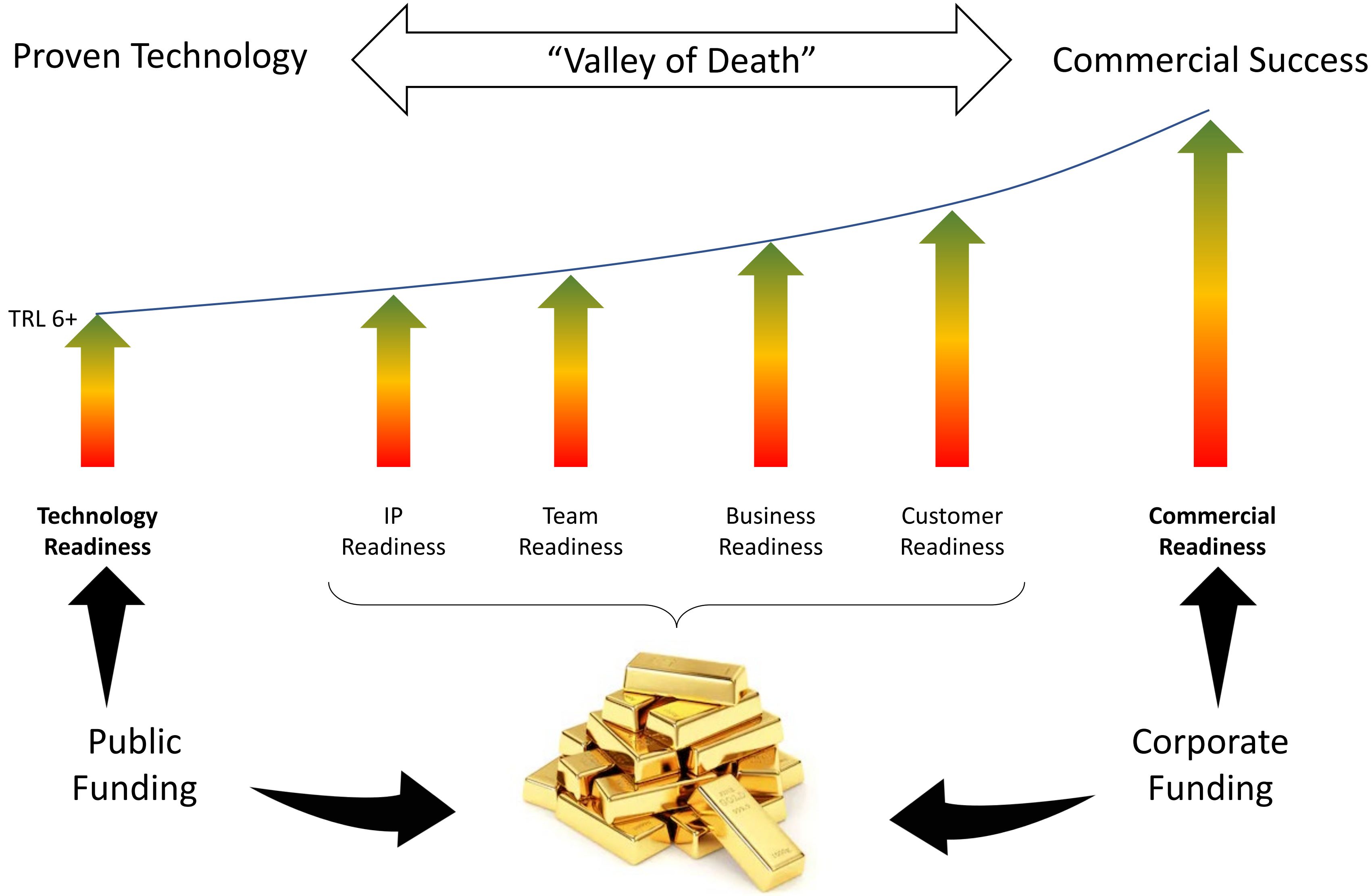


Technology Readiness

Commercial Success

You are here

Does Proven technology = commercial success?



Proven Technology

“Valley of Death”

Commercial Success

TRL 6+

Technology Readiness

IP Readiness

Team Readiness

Business Readiness

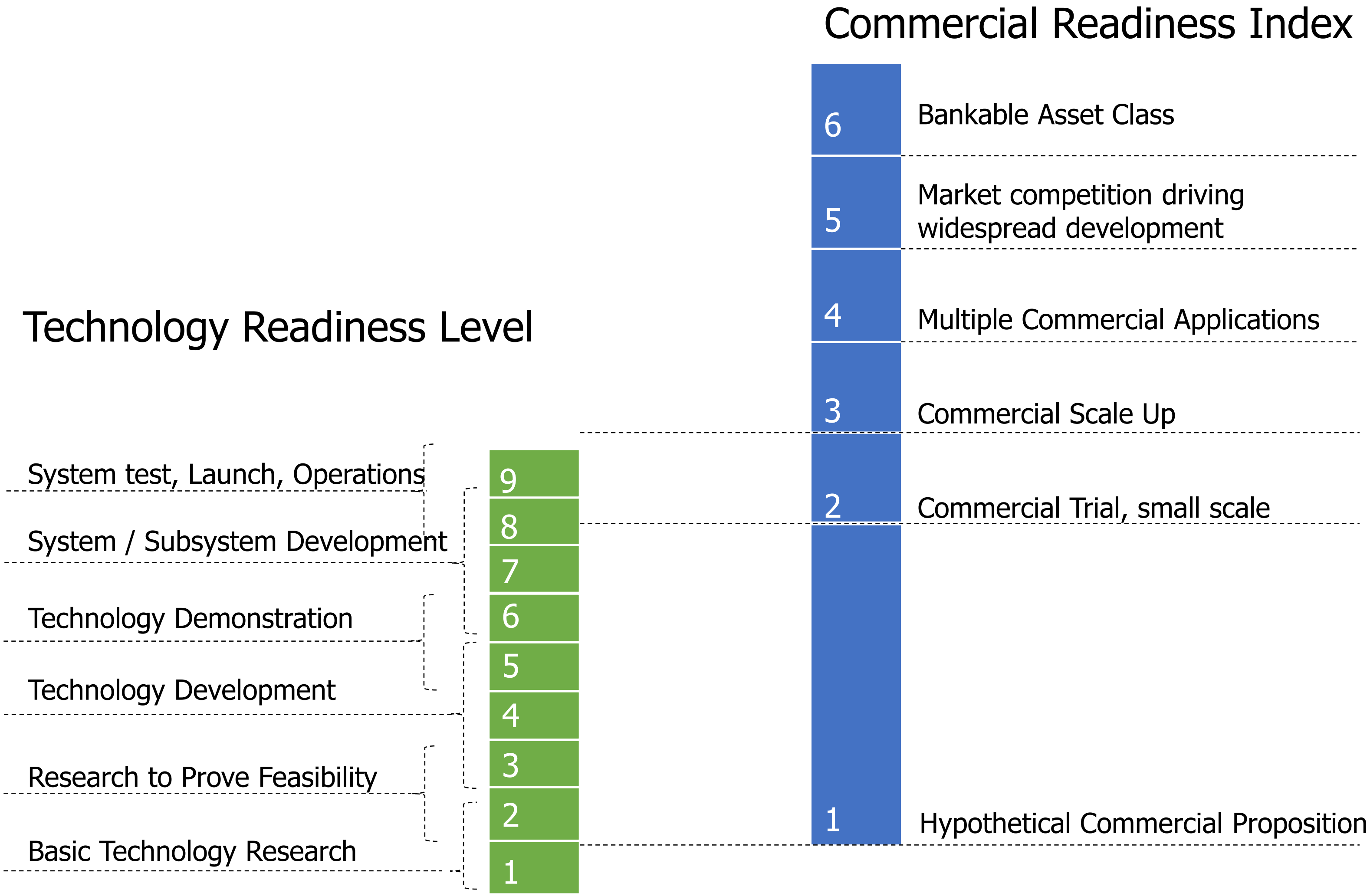
Customer Readiness

Commercial Readiness

Public Funding

Corporate Funding

How do you measure readiness?



Commercial Readiness Index

6 Bankable Asset Class

5 Market competition driving widespread development

4 Multiple Commercial Applications

3 Commercial Scale Up

2 Commercial Trial, small scale

1 Hypothetical Commercial Proposition

Technology Readiness Level

System test, Launch, Operations

System / Subsystem Development

Technology Demonstration

Technology Development

Research to Prove Feasibility

Basic Technology Research

https://arena.gov.au/assets/2014/02/Commercial-Readiness-Index.pdf

How to traverse the “valley of death”?

Think like a supplier:

- Guaranteed performance level
- Warranty and reliability
- Competitive awareness

Think like a contractor:

- Lowest cost option
- Construction schedule
- Integration

Think like an owner:

- Performance
- Operations & Maintenance costs
- Availability

Think like an investor/lender:

- High rate of return
- Low risk of failure

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What to consider early in development?

Operability

- Means to monitor operating limits in real-time
- Effects of system interactions
- Automatic "operator-proof" control
- Equipment sizing for startup /shutdown

Scalability

- Material availability
- Production-scale quality management
- Construction methods
- Heat loss
- Margin for guaranteed performance

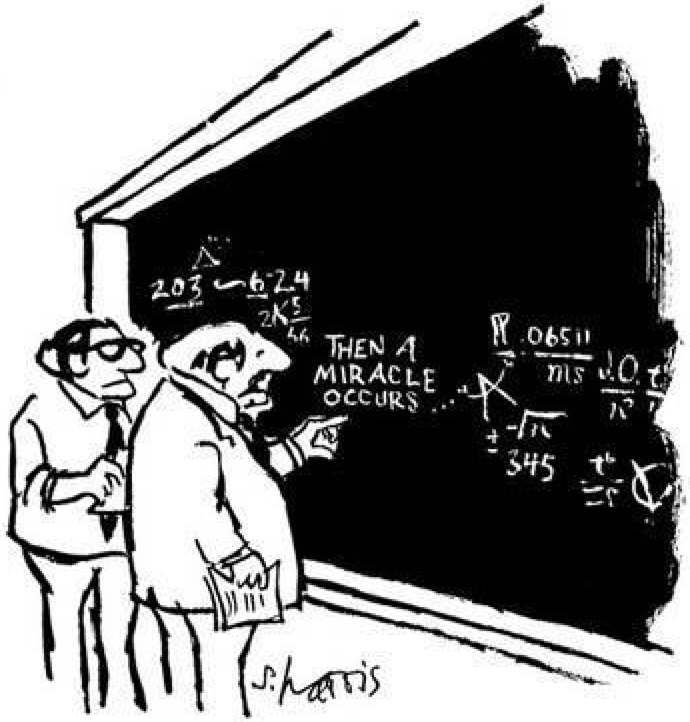
Market Adoption

- Competition
- Standards for design and acceptance testing
- Initial investment
- Health, safety, & environmental risks
- Failure modes
- "Lessons learned"

Cost

- Quality of potential supplier's quotes
- Completeness of requirements
- System-level thermo-economic optimization
- Performance margin
- Realistic pro forma financial assumptions

And what to avoid…



Thank You!