CSP Gen 3 Roadmap

Gas-Phase Receiver Technology Pathway

Background and Research Overview

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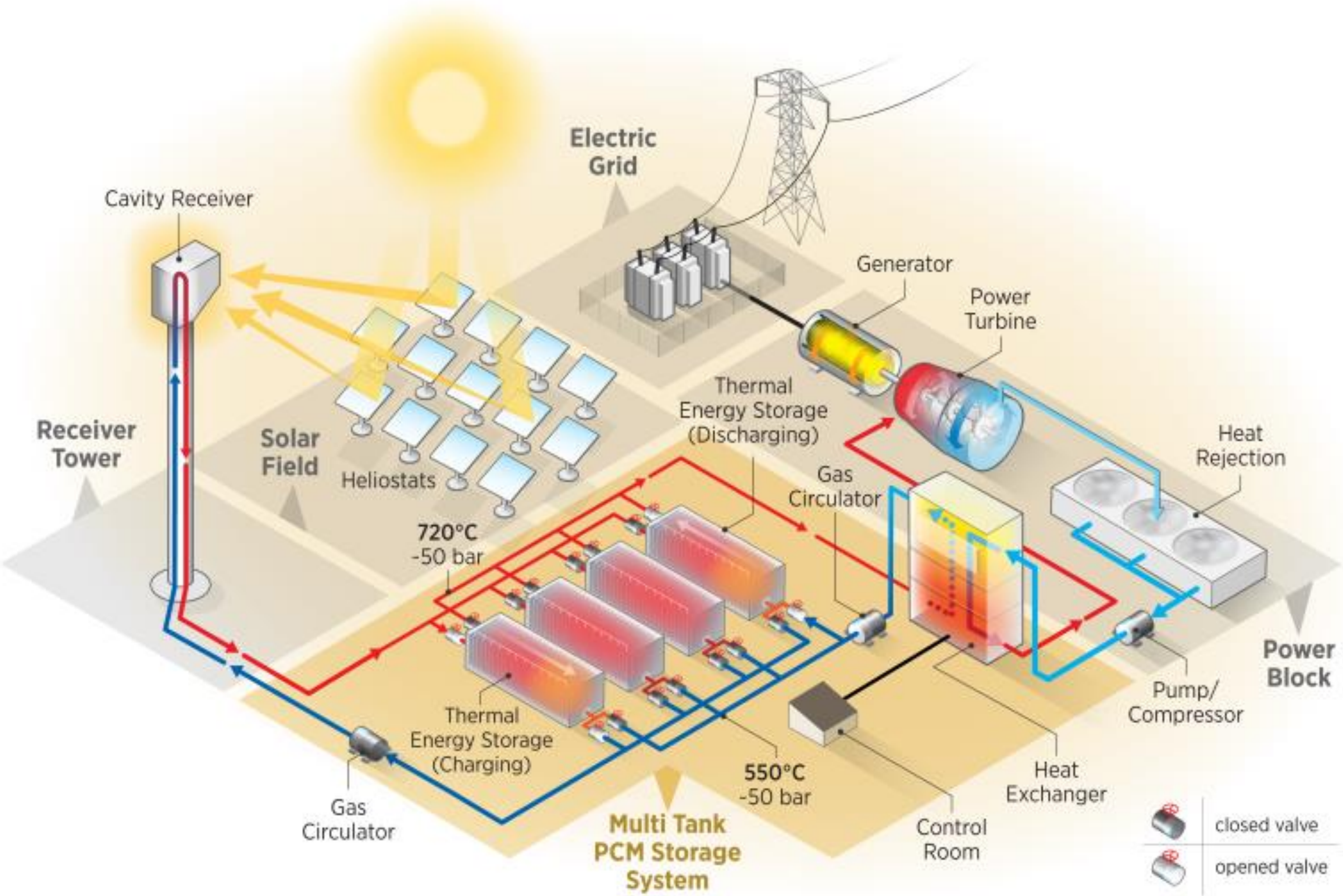
Gas-Phase (GP) Technology Overview

- **Gas-phase heat transfer fluid**
  - Behaves as an ideal gas
  - Operates in the range of 60-120 bar
  - Balances wall thickness requirements with heat transfer characteristics
- **Closed-loop configuration**
  - Uses gas circulators
  - Enables high thermodynamic efficiency by allowing power cycle to accept heat at a high average temperature.
  - Gas-to-gas heat exchanger between receiver/TES loop and s-CO2 power cycle loop.
- **Indirect thermal energy storage**
  - Secondary storage media
  - Enables a variety of TES technologies
- **Power generation decoupled from production**
  - Allows the system to dispatch to demand or price spikes without affecting the energy collection subsystem.
  - Simplifies operations, reduces grid costs, and improves project financial return
- **Receiver comprised of multiple parallel flow paths**

Gas-Phase Receiver System with PCM Storage



Features of the GP Pathway

Advantages

- **Thermally stable**
  - No phase change
  - Eliminates heat-trace, attrition, chemistry management equipment
  - Simplifies system startup and shutdown
- **Inert**
  - Reduces corrosion
  - Minimal environmental or safety hazards
- **Low cost and high thermal efficiency**
  - 89-95% receiver, <200$/kWt
- **Builds on existing designs**
- **Simple primary heat-exchanger**
- **Enables advanced TES concepts**

Challenges

- **Inferior heat-transfer to liquids**
  - Optimization of operating pressure
  - Transient response sensitivity
- **Indirect TES technology**
  - System integration
- **Power consumption for fluid circulation**
- **Selection of appropriate pressure and temperature targets**
  - Balance wall material cost with parasitic losses
- **Flow path complexity**

Why hasn't this been pursued more aggressively?

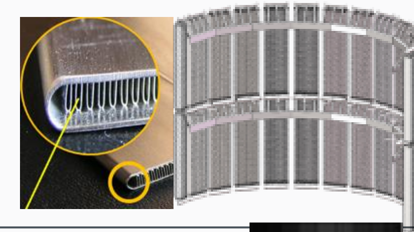
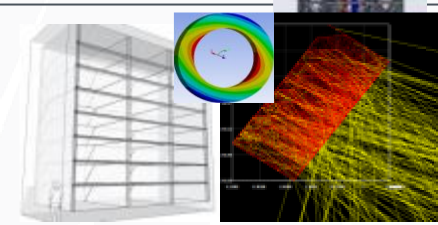
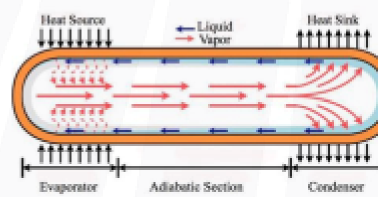
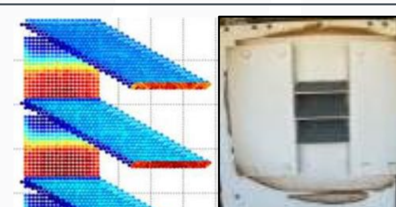
- Superior performance of liquid-phase HTF's at lower temperature
- Focus on air-Brayton hybridization and solar fuels for gas receiver technologies
- Insufficient motivation given limits of steam Rankine cycle
- Insufficient apatite for long-range CSP

Recent enabling developments

- High-pressure s-CO_2 receiver technology
- PCM storage concepts (e.g., graphite-impregnated molten salt)
- s-CO_2 power cycle
- Materials advances

Subsystems and research areas

1. Receiver design
2. Heat transfer fluid and circulation subsystem
3. Thermal energy storage subsystem
4. System integration

Receiver Technology	Achievements	Status
Brayton Energy	• Novel absorber geom. • 715-750°C HTF out • 250 bar, CO_2 • 90.6-94.9 % efficient	• Absorber commercialized as HX • Demonstrated panel on-sun • Follow-on APOLLO project 
OSU Oregon State University	• Microchannel design • 1-1.4 MWt/m^2 flux • 720°C, 250 bar CO_2 • Rad., conv loss <5%	• SunShot seedling project • Micro-lamination fabrication demonstrated 
NREL National Renewable Energy Laboratory	• Internal cellular geom. • 92-94.5% efficient • 650°C, 200 bar • Modeling tools	• Lab-scale experimental model validation • Project completed 
Los Alamos National Laboratory	• Continuous solid-state heat pipe system • Liquid Na or K HTF • 600-1000°C	• Experimental demo for linear system • Development underway for power tower applications 
Sandia National Laboratories	• Bladed geometry • 97% modeled solar absorptivity	• Sandia-funded project • Demonstrated on-sun, air HTF • Experiment shows 6% efficiency advantage over flat receiver 

Receiver development needs

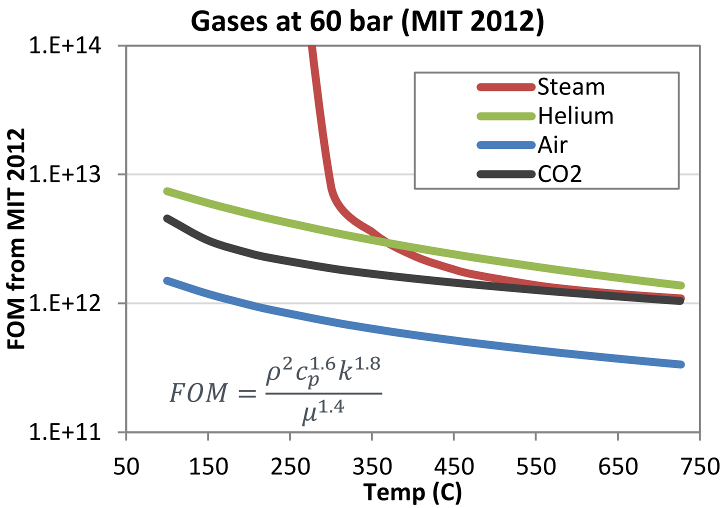
- Adapt existing receiver designs
  - Alternate HTF (if needed)
  - Lower operating pressure, higher temperature
  - Identify likely modes of failure
  - Improve understanding of off-design, transient response
- Co-optimization of heliostat field and receiver
- Mid-scale prototype demonstration
  - Previous work has had limited on-sun testing
- Cycling and fatigue analysis
  - Careful understanding of allowable heat flux, impact of fatigue and creep stress
- Fluid flow design
  - Ensure stability, avoid hot spots

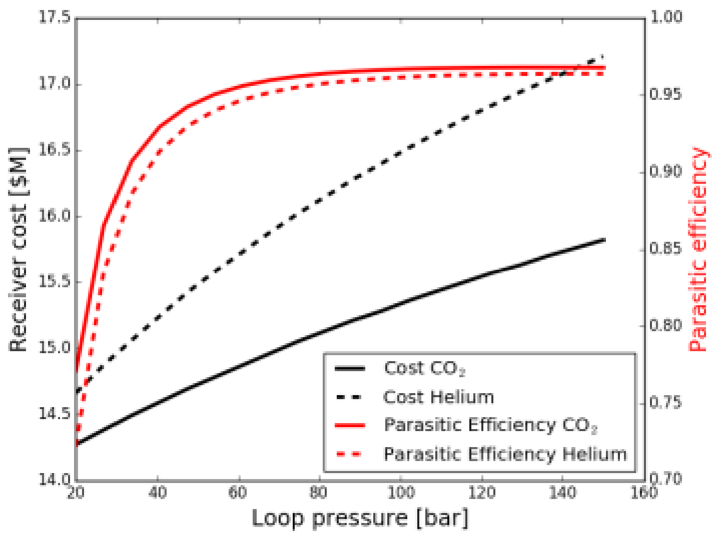
Heat Transfer Fluid and Circulator Subsystem

Indirect configuration introduces a degree of freedom in HTF composition

Related work

- Fossil: Air, ≤30 MWe
  - Considered size of the turbomachine, heat exchangers, casings, ducts, and the external fossil-fired heater
  - Favorable simplicity, conventionality, and cost
- Nuclear: Helium
  - Considered reactor-coolant and power-conversion system
  - Favorable chemical inertness, immunity to radiation effects, cycle compatibility, power scalability





Additional HTF Considerations

- Corrosivity
  - Helium is chemically inert under proposed conditions
  - Air or CO_2 require evaluation
    - Work to date has suggested Haynes 230 as a reasonable selection for CO_2 at 700°C
- Cost
  - Helium more expensive than other choices

> A 35 MWt receiver and 96 MWh of storage with a 30% HTF volumetric (void) fraction would require approximately 175-m^3 of helium inventory at 60 bar, and would cost about $77K.

- Circulator design
  - CO_2 circulator custom-designed, but is readily achievable
  - Nuclear industry has explored helium for use in Very High Temperature Reactor (VHTR)

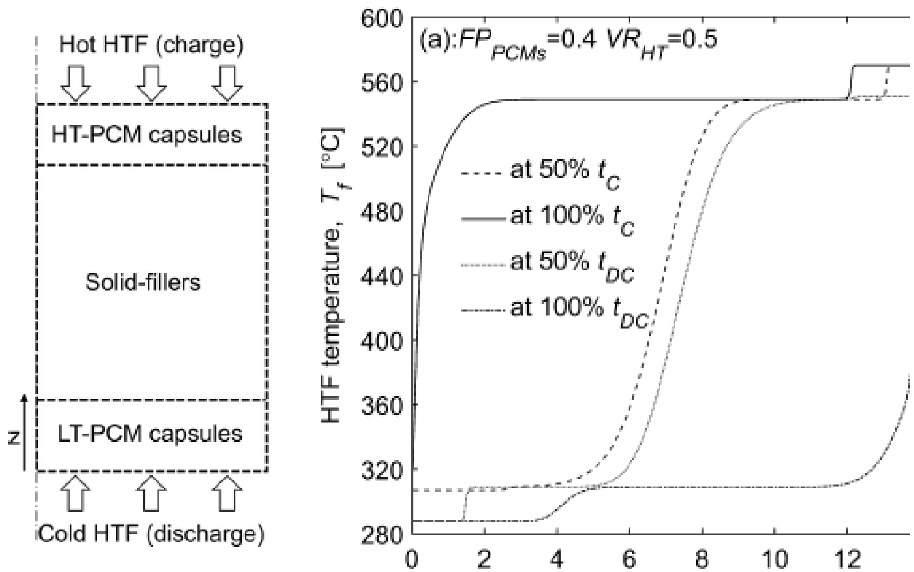
HTF and circulator development needs

- HTF selection and optimization based on cost, parasitic requirements, corrosion
- Methods for reducing transport piping cost
- Circulator turbomachinery selection and design

Thermal Energy Storage Subsystem

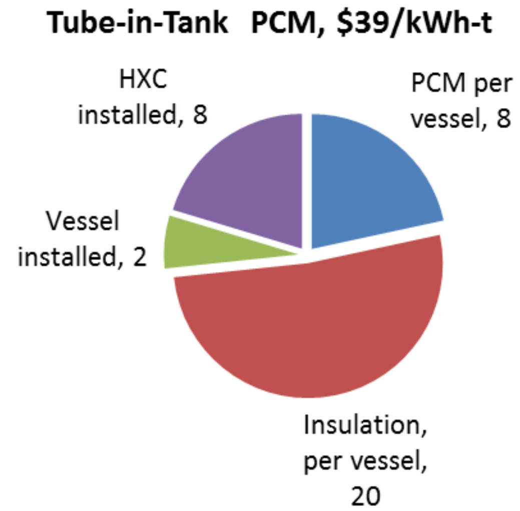
- GP pathways allows adoption of lower-cost, higher energy density TES options
- Review indicates PCM based on chloride salts as viable near term, potentially low cost
- Chloride features:
  - Range of blends possible
  - Effective within 150-200K ΔT
- Challenges:
  - Heat transfer into salt
  - Need to form layers of material to maintain temperature profile stability
- Three concepts explored
  - ~~Encapsulated pressurized PCM~~
  - PCM with embedded tubes
  - Sensible heat particle storage

Salt Blend (wt fractions)	Melting Point (C)	Heat of Fusion (J/g)	Cost ($/kg)
NaCl/LiCl (0.34 / 0.66)	554	399	4.6
NaCl/KCl (0.434 / 0.566)	659	417[?]	0.3
$MgCl_2$	714	454	0.4
KCl	771	353	0.4
NaCl	801	482	0.1



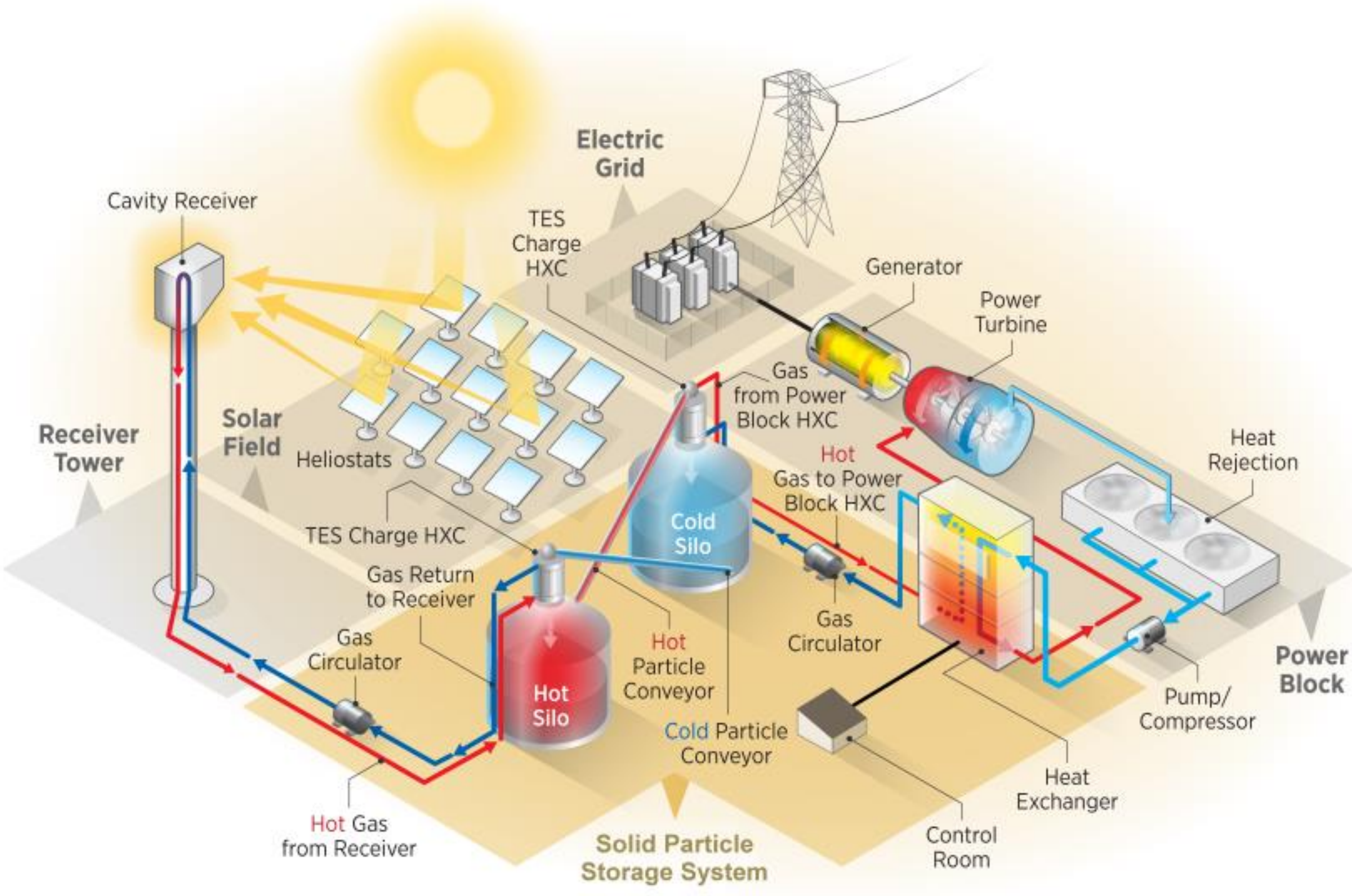
Tube-in-Tank PCM TES

- HTF piping penetrates a vessel filled with PCM
- Graphite foam with chloride-salt PCMs
  - Mitigates low conductivity
  - Factor of 12 reduction in piping
  - Maintains a sealed, inert environment to avoid corrosion
  - Minimal PCM interaction with metallic TES system components
- Abengoa Solar: PCM storage offers significant opportunity for cost reduction in CSP systems
- Opportunity for optimization of vessel insulation and heat exchanger design
- Pressure drop within the system must also be carefully investigated



Argonne National Laboratory test latent PCM TES system [https://www.anl.gov/articles/argonne-technology-puts-solar-power-work-all-night-long]

Gas-Phase Receiver System with Particle Storage



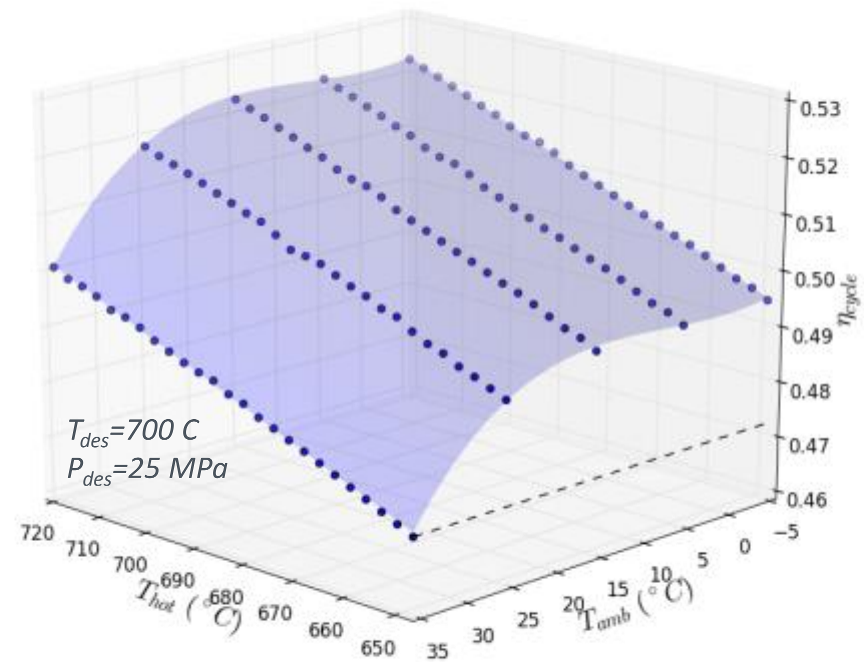
TES Development needs

- Determine PCM-embedded piping/heat-exchanger designs to allow for effective heat transfer and minimize pressure drop.
- Identify and characterize the preferred PCM salts for use with a cascaded PCM design
- Model the behavior of a multi-module PCM design to estimate the thermal effectiveness and overall energy/exergy efficiency of the system throughout annual simulations.
- Select and test internal insulation in contact with PCM salt freeze/thaw cycles.
- Select and test heat-exchanger alloy in contact with salt melt.
- Evaluate scalability of TES tube-in-tank system designs; build and test prototypes to demonstrate long-term performance reliability.
- Undertake design of a gas-phase receiver/particle-TES system to detail potential advantages related to performance and risk of other system designs.

System Integration

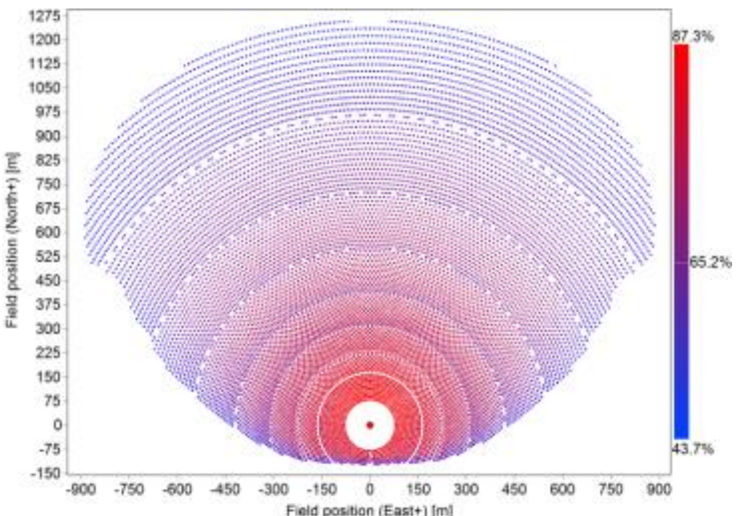
- Understand the implications of integrating PCM TES, GP receiver, power cycle
- Identify control and off-design challenges
- Characterize annual productivity

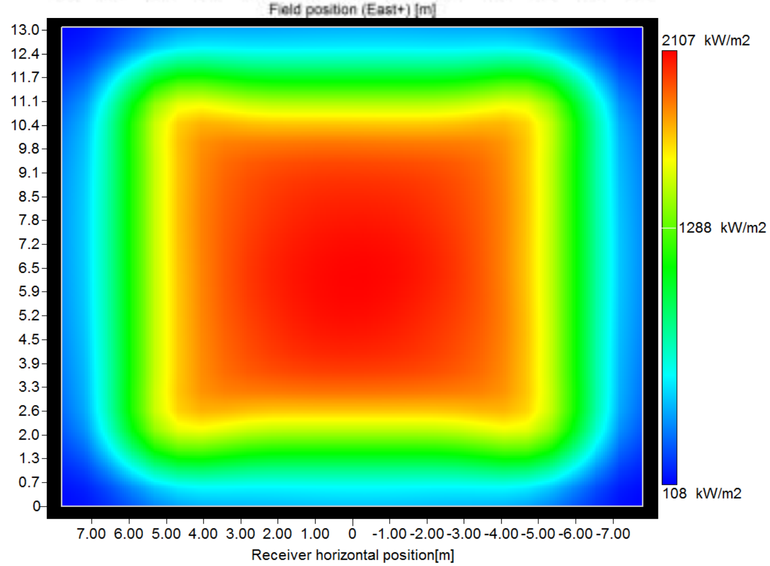
- Power cycle integration
  - Not a unique challenge to GP technologies
  - Off-design more of an issue for PCM, temperature profile changes with charge state
  - Ambient response more significant than hot side T



System Sizing and Field Design

Example solar field design for 50 MWe turbine, SM 2.5





	Units	Value
Receiver height	M	13.1
Receiver width	M	15.6
Aperture tilt angle	°	-44.0
Tower height	M	160.0
Single heliostat area	m^2	36.0
Heliostat focusing type		Ideal
Total heliostat area	m^2	406,296
Simulated heliostat count	-	11,286
Reference simulation	Spring equinox at noon	
Power incident on field	kW	385,981
Power absorbed by the receiver	kW	262,773
Power absorbed by HTF	kW	250,943
Cosine efficiency	%	90.1
Blocking/shading efficiency	%	98.5
Attenuation efficiency	%	93.4
Heliostat reflectivity and soiling	%	90.3
Image intercept efficiency	%	91.0
Solar-field optical efficiency	%	68.1
Average incident flux	kW/m^2	1288.3

Valve Design and Testing

- GP + PCM TES depends on reliable switching valves that can operate in high-temperature/high-pressure situations

Previous work by UW-Madison and Flowserve explores options for regenerative HX

- Considered single-actuating globe valves, 3-way valves, and rotary ball valves
- Selected a valve that is believed to be suitable for their application and are proposing to test the design
- Excepting temperature, GP pathway conditions are less rigorous

Commercial valve options are rated to 550°C and up to 170 bar with 316SS.

System and integration Development needs

- Develop component performance models for both design and off-design conditions
  - Predict thermodynamic fluid states, heat-transfer behavior, and relevant mechanical considerations, and consolidate into a system-level model
- Determine heliostat field layout and flux control methods suitable for GP receivers with a commercially relevant module size
- Select and characterize HTF-to-sCO_2 heat-exchanger technology
- Selection and testing of high-pressure/high-temperature values
  - Assess code status (e.g., ASME B16.34) of alloy choices for high-temperature valves

Summary

Topic area	Needed expertise	Components
Receiver	(Modeling and/or measurement) • Flow control • Flux and optical performance • Thermal stress and fatigue • Thermal loss • Performance simulation	• Absorber • Heat shielding, surface coatings • Flow distributors and valves • Welds and joints • Mechanical supports • Instrumentation
Thermal storage	• Heat transfer for charge and discharge • PCM structure design • Materials; salts • Salt corrosion • Cascaded phase change	• Gas-to-PCM heat exchanger • Gas-to-particle heat exchanger • Containment vessel • Internal/external insulation • Particle conveyor
HTF	• Turbomachinery design • High-pressure helium, CO_2, argon, etc. containment and transport • Piping, fluid flow	• Circulator • High-temperature valving • High-temperature insulation, internal and external
System integration	• Large project integration • Controls • Operations and dispatch optimization • System modeling • Heliostat field design and control • Cost analysis	• Gas-to-gas heat primary heat exchanger • Hot and cold side TES valves