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
<table>
<thead>
<tr>
<th>Receiver Technology</th>
<th>Achievements</th>
<th>Status</th>
</tr>
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</table>
| Brayton Energy      | • Novel absorber geom.  
• 715-750°C HTF out  
• 250 bar, CO₂  
• 90.6-94.9 % efficient | • Absorber commercialized as HX  
• Demonstrated panel on-sun  
• Follow-on APOLLO project |
| OSU                 | • Microchannel design  
• 1-1.4 MWt/m² flux  
• 720°C, 250 bar CO₂  
• Rad., conv loss <5% | • SunShot seedling project  
• Micro-lamination fabrication demonstrated |
| NREL                | • Internal cellular geom.  
• 92-94.5% efficient  
• 650°C, 200 bar  
• Modeling tools | • Lab-scale experimental model validation  
• Project completed |
| Los Alamos          | • 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

**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

\[
FOM = \frac{\rho c_p}{\mu^{1.4}}
\]

*Gases at 60 bar (MIT 2012)*

*Indirect configuration introduces a degree of freedom in HTF composition*
Additional HTF Considerations

• Corrosivity
  • Helium is chemically inert under proposed conditions
  • Air or CO₂ require evaluation
    • Work to date has suggested Haynes 230 as a reasonable selection for CO₂ 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-m³ of helium inventory at 60 bar, and would cost about $77K.

• Circulator design
  • CO₂ 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 $\Delta T$
- 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

<table>
<thead>
<tr>
<th>Salt Blend (wt fractions)</th>
<th>Melting Point (°C)</th>
<th>Heat of Fusion (J/g)</th>
<th>Cost ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl/LiCl (0.34 / 0.66)</td>
<td>554</td>
<td>399</td>
<td>4.6</td>
</tr>
<tr>
<td>NaCl/KCl (0.434 / 0.566)</td>
<td>659</td>
<td>417</td>
<td>0.3</td>
</tr>
<tr>
<td>MgCl$_2$</td>
<td>714</td>
<td>454</td>
<td>0.4</td>
</tr>
<tr>
<td>KCl</td>
<td>771</td>
<td>353</td>
<td>0.4</td>
</tr>
<tr>
<td>NaCl</td>
<td>801</td>
<td>482</td>
<td>0.1</td>
</tr>
</tbody>
</table>
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 $T$

$T_{des} = 700 \, ^\circ C$
$P_{des} = 25 \, MPa$
## System Sizing and Field Design

Example solar field design for 50 MWe turbine, SM 2.5

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver height</td>
<td>M</td>
<td>13.1</td>
</tr>
<tr>
<td>Receiver width</td>
<td>M</td>
<td>15.6</td>
</tr>
<tr>
<td>Aperture tilt angle</td>
<td>°</td>
<td>-44.0</td>
</tr>
<tr>
<td>Tower height</td>
<td>M</td>
<td>160.0</td>
</tr>
<tr>
<td>Single heliostat area</td>
<td>m²</td>
<td>36.0</td>
</tr>
<tr>
<td>Heliostat focusing type</td>
<td></td>
<td>Ideal</td>
</tr>
<tr>
<td>Total heliostat area</td>
<td>m²</td>
<td>406,296</td>
</tr>
<tr>
<td>Simulated heliostat count</td>
<td></td>
<td>11,286</td>
</tr>
<tr>
<td>Reference simulation</td>
<td></td>
<td>Spring equinox at noon</td>
</tr>
<tr>
<td>Power incident on field</td>
<td>kW</td>
<td>385,981</td>
</tr>
<tr>
<td>Power absorbed by the receiver</td>
<td>kW</td>
<td>262,773</td>
</tr>
<tr>
<td>Power absorbed by HTF</td>
<td>kW</td>
<td>250,943</td>
</tr>
<tr>
<td>Cosine efficiency</td>
<td>%</td>
<td>90.1</td>
</tr>
<tr>
<td>Blocking/shading efficiency</td>
<td>%</td>
<td>98.5</td>
</tr>
<tr>
<td>Attenuation efficiency</td>
<td>%</td>
<td>93.4</td>
</tr>
<tr>
<td>Heliostat reflectivity and soiling</td>
<td>%</td>
<td>90.3</td>
</tr>
<tr>
<td>Image intercept efficiency</td>
<td>%</td>
<td>91.0</td>
</tr>
<tr>
<td>Solar-field optical efficiency</td>
<td>%</td>
<td>68.1</td>
</tr>
<tr>
<td>Average incident flux</td>
<td>kW/m²</td>
<td>1288.3</td>
</tr>
</tbody>
</table>
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

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<tr>
<th>Topic area</th>
<th>Needed expertise</th>
<th>Components</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Receiver</strong></td>
<td>(Modeling and/or measurement)</td>
<td>• Absorber</td>
</tr>
<tr>
<td></td>
<td>• Flow control</td>
<td>• Heat shielding, surface coatings</td>
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<tr>
<td></td>
<td>• Flux and optical performance</td>
<td>• Flow distributors and valves</td>
</tr>
<tr>
<td></td>
<td>• Thermal stress and fatigue</td>
<td>• Welds and joints</td>
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<tr>
<td></td>
<td>• Thermal loss</td>
<td>• Mechanical supports</td>
</tr>
<tr>
<td></td>
<td>• Performance simulation</td>
<td>• Instrumentation</td>
</tr>
<tr>
<td><strong>Thermal storage</strong></td>
<td>• Heat transfer for charge and discharge</td>
<td>• Gas-to-PCM heat exchanger</td>
</tr>
<tr>
<td></td>
<td>• PCM structure design</td>
<td>• Gas-to-particle heat exchanger</td>
</tr>
<tr>
<td></td>
<td>• Materials; salts</td>
<td>• Containment vessel</td>
</tr>
<tr>
<td></td>
<td>• Salt corrosion</td>
<td>• Internal/external insulation</td>
</tr>
<tr>
<td></td>
<td>• Cascaded phase change</td>
<td>• Particle conveyor</td>
</tr>
<tr>
<td><strong>HTF</strong></td>
<td>• Turbomachinery design</td>
<td>• Circulator</td>
</tr>
<tr>
<td></td>
<td>• High-pressure helium, CO$_2$, argon, etc. containment and transport</td>
<td>• High-temperature valving</td>
</tr>
<tr>
<td></td>
<td>• Piping, fluid flow</td>
<td>• High-temperature insulation, internal and external</td>
</tr>
<tr>
<td><strong>System integration</strong></td>
<td>• Large project integration</td>
<td>• Gas-to-gas heat primary heat exchanger</td>
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<tr>
<td></td>
<td>• Controls</td>
<td>• Hot and cold side TES valves</td>
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<tr>
<td></td>
<td>• Operations and dispatch optimization</td>
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<tr>
<td></td>
<td>• System modeling</td>
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<td></td>
<td>• Heliostat field design and control</td>
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<td></td>
<td>• Cost analysis</td>
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