sCO₂ Power Cycle with Integrated Thermochemical Energy Storage Using an MgO-Based sCO₂ Sorbent in Direct Contact with Working Fluid

DE-EE0008126
CSP Program Summit
Oakland, CA
March 18-19, 2019
Program summary

- Thermochemical energy storage using MgO+CO$_2$=MgCO$_3$ reversible reaction with sCO$_2$ power cycle
- CO$_2$ generated/consumed stored by sCO$_2$ inventory control system (ICS)
- Reactor and ICS storage in underground pressure vessel
- Overall technology requirements:
  - >50% cycle thermodynamic efficiency
  - >95% exergetic storage efficiency
  - Storage system cost < $15/kWth
Program goals

- Refine/improve MgO sorbent performance, complete design of commercial-scale reactor / storage system
- Conduct lab-scale test of integrated sCO₂ loop / TCES system
- Complete techno-economic analysis of full-scale (100MWe) power block + TCES system
SR tested 26 MgO based lab-scale sorbents in HTR for capacity, durability and production cost.

- Absorption capacity: 2-6 hr charge/discharge cycles at pressures of 100-300 atm (600-670°C), > 0.25 g CO₂/g sorbent
- Degradation: < 1% loss in capacity over 25 cycles
- Cost of sorbent material (including processing) plus containment less than 9$/kWh_th.

Identified “MgO coated with 40wt% Na₂CO₃ promoter (MC30P_coated_40wt%)” for large batch sorbent production (~100kg) for lab prototype system testing.

<table>
<thead>
<tr>
<th>sample name</th>
<th>weight gain</th>
<th>Energy density</th>
<th>sorbent containment</th>
<th>total (&lt;9)</th>
<th>cost ($/kWh_th)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E13 pellet 0% promoter</td>
<td>0.125</td>
<td>398</td>
<td>5.89</td>
<td>3.21</td>
<td>9.11</td>
</tr>
<tr>
<td>E13 pellet 10% promoter</td>
<td>0.165</td>
<td>581</td>
<td>4.98</td>
<td>2.20</td>
<td>7.18</td>
</tr>
<tr>
<td>E13 pellet 20% promoter</td>
<td>0.228</td>
<td>872</td>
<td>3.95</td>
<td>1.47</td>
<td>5.42</td>
</tr>
<tr>
<td>E13 pellet 22% promoter</td>
<td>0.188</td>
<td>733</td>
<td>4.85</td>
<td>1.74</td>
<td>6.60</td>
</tr>
<tr>
<td>E13 pellet 40% promoter</td>
<td>0.211</td>
<td>941</td>
<td>4.84</td>
<td>1.36</td>
<td>6.19</td>
</tr>
<tr>
<td>E19(older) pellet 40% promoter</td>
<td>0.330</td>
<td>1474</td>
<td>1.23</td>
<td>0.87</td>
<td>2.10</td>
</tr>
<tr>
<td>SR1.1 powder 0% promoter</td>
<td>0.717</td>
<td>1139</td>
<td>1.02</td>
<td>1.12</td>
<td>2.15</td>
</tr>
<tr>
<td>SR1.1 pellet 0% promoter</td>
<td>0.351</td>
<td>761</td>
<td>2.09</td>
<td>1.68</td>
<td>3.77</td>
</tr>
<tr>
<td>SR1.1 powder 10% promoter</td>
<td>0.833</td>
<td>1537</td>
<td>0.99</td>
<td>0.83</td>
<td>1.82</td>
</tr>
<tr>
<td>SR1.1 pellet 10% promoter</td>
<td>0.574</td>
<td>1424</td>
<td>1.44</td>
<td>0.90</td>
<td>2.33</td>
</tr>
<tr>
<td>SR1.1 powder 20% promoter</td>
<td>0.825</td>
<td>1282</td>
<td>1.09</td>
<td>1.00</td>
<td>2.09</td>
</tr>
<tr>
<td>SR1.1 pellet 20% promoter</td>
<td>0.615</td>
<td>1204</td>
<td>1.46</td>
<td>1.06</td>
<td>2.52</td>
</tr>
<tr>
<td>SR1.1 powder 40% promoter</td>
<td>0.826</td>
<td>865</td>
<td>1.23</td>
<td>1.48</td>
<td>2.71</td>
</tr>
<tr>
<td>SR1.1 pellet 40% promoter</td>
<td>0.723</td>
<td>1299</td>
<td>1.41</td>
<td>0.98</td>
<td>2.39</td>
</tr>
<tr>
<td>E3 pellet 20% promoter</td>
<td>0.149</td>
<td>500</td>
<td>6.03</td>
<td>2.55</td>
<td>8.59</td>
</tr>
<tr>
<td>E4 pellet 20% promoter</td>
<td>0.300</td>
<td>778</td>
<td>3.00</td>
<td>1.64</td>
<td>4.64</td>
</tr>
<tr>
<td>E5 pellet 20% promoter</td>
<td>0.069</td>
<td>163</td>
<td>13.04</td>
<td>7.86</td>
<td>20.90</td>
</tr>
<tr>
<td>E6 pellet 20% promoter</td>
<td>0.149</td>
<td>293</td>
<td>6.05</td>
<td>4.36</td>
<td>10.41</td>
</tr>
<tr>
<td>E19(new) pellet 20% promoter</td>
<td>0.245</td>
<td>420</td>
<td>3.68</td>
<td>3.04</td>
<td>6.72</td>
</tr>
<tr>
<td>E26 pellet 20% promoter</td>
<td>0.255</td>
<td>437</td>
<td>3.54</td>
<td>2.92</td>
<td>6.46</td>
</tr>
<tr>
<td>SR1.1Pcal_coated_40wt%</td>
<td>0.772</td>
<td>2081</td>
<td>1.32</td>
<td>0.61</td>
<td>1.99</td>
</tr>
<tr>
<td>MC30P_coated_40wt%</td>
<td>0.735</td>
<td>1968</td>
<td>1.39</td>
<td>0.65</td>
<td>2.04</td>
</tr>
<tr>
<td>Mg-citrateP_coated_carbon_sintered_40wt%</td>
<td>0.731</td>
<td>1735</td>
<td>1.39</td>
<td>0.74</td>
<td>2.13</td>
</tr>
<tr>
<td>Mg-citrateP_coated_carbon_40wt%</td>
<td>0.789</td>
<td>1699</td>
<td>1.29</td>
<td>0.75</td>
<td>2.04</td>
</tr>
<tr>
<td>Mg-citrateP_carbon_sintered_40wt%</td>
<td>0.668</td>
<td>1586</td>
<td>1.52</td>
<td>0.81</td>
<td>2.33</td>
</tr>
<tr>
<td>Mg-citrateP_carbon_40wt%</td>
<td>0.739</td>
<td>1739</td>
<td>1.38</td>
<td>0.73</td>
<td>2.11</td>
</tr>
</tbody>
</table>
Samples are individually wrapped in steel mesh and binded with copper wire, after test the meshed is substantially oxidized.

Cold side including pressure transducer, two thermocouple probes, RTD, fill valve and cold vessel with thermoelectric modules and heat sinks.
Lab Scale sCO$_2$/TCES Test Loop

- Lab scale test loop design is complete
- Design Target: 700°C, 20 MPa, 0.2 kg/s CO$_2$ flow rate
- Stage-I testing and commissioning (without HTR and TCES) of sCO$_2$ test loop is complete.
  - Max CO$_2$ Temperature = 522°C (Stage 1 heater design point)
  - Max Coil Temperature = 594°C
  - Max Heater Element Temperature = 942°C
  - Max Pump Discharge Pressure = 11.5 MPa (fixed-orifice limit)
Lab Scale Testing: sCO$_2$ Radiant Heaters

- **Low Temperature Radiant Heater (PHX1)**
  - Material: TP316H
  - Size: 1”OD x 0.120”wall
  - Spec: B31.3 A269
  - 4-pass Config. approx. 27 linear ft
  - Max Coil Temperature YTD: 594°C
  - CO$_2$ Outlet Temp: 522°C

- **High Temperature Radiant Heater (PHX2)**
  - Material: N07740
  - Spec: B31.1 Code Case 190
  - Size: 1.25”OD x 0.156”wall
  - Coil Config. Approx. 72 linear ft
  - Max conditions
    - Max Temp= 759°C
    - Max Pressure= 20.68MPa
    - Design Flow= 0.2 - 0.3kg/s
Lab Scale Testing: TCES Reactor Design

- Lab scale reactor design is complete for phase-II testing
- Design based on planned charging/ discharging rate of 20kW with a cycle time of approximately 2 hours

  - Reactor Body
    - 24” Schd. 160 A106 Gr. B Pipe
    - Design pressure 20 MPa
    - Approx. Dry Weight: 7000lb
### Full-scale (100MWe) TCES + sCO$_2$ Power Cycle Transient Modeling

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sorbent particle diameter</td>
<td>3 mm</td>
</tr>
<tr>
<td>Sorbent bed void fraction</td>
<td>0.5</td>
</tr>
<tr>
<td>Reactor frontal diameter</td>
<td>20 m</td>
</tr>
<tr>
<td>Reactor length</td>
<td>20 m</td>
</tr>
<tr>
<td>Active sorbent density</td>
<td>6171.3 mol/m³</td>
</tr>
</tbody>
</table>

![Diagram of Solar Receiver and TCES Reactor](image)

**Inventory Ctrl Sys**

**ACC**

**LT-Recp**

**HT-Recp**

**HT-Comp-DT**

**LT-Comp-DT**

**Generator**

---

Echogen Power Systems
TCES + sCO$_2$ Power Cycle Transient Modeling

- Drive turbine throttle valve CO$_2$ high pressure control = 30.4 MPa
- System low pressure controlled using inventory control system = 10.21 MPa
TCES + sCO₂ Power Cycle Transient Modeling

- CO₂ Inventory Ctrl Flow Rate
- TCES Inlet Temperature

- Coverage Fraction
- MgCO₃
- MgO
- TCES Inlet Temperature

- PT Power
- TCES Inlet Temperature

- TCES Temperatures
- Inlet
- Outlet
Summary

- During BP1, SR tested and identified a MgO based sorbent for large-batch production (100kg) for lab scale testing of integrated sCO$_2$/TCES system in BP2.
- Stage-I testing and commissioning of sCO$_2$ test loop is complete.
- Stage-II testing of high temperature heater is slightly delayed due to manufacturer delay in Inconel 740H tube supply.
- Stage-III testing during BP2 involves complete testing of lab scale integrated sCO$_2$ loop/TCES reactor test loop.
- The result of the transient simulation indicated that with proper cycle design, and TCES reactor capacity, the SunShot targets of 100MW capacity, and 10hours storage could be met.
- Operation and control of the cycle appears feasible, and based on the kinetics of the sorbent/CO$_2$ reaction, adequate charging and generation rates are achievable.
Stage-I sCO$_2$ Loop Testing: PHX1
Stage-I $\text{sCO}_2$ Loop Testing: Pump and Recuperator

- CAT Pump
  - Model: 6821K.CO2
  - Rated Flow: 25GPM
  - Max Discharge Pressure: 20.7 MPa
  - Motor Size: 30HP

- Manufacturer: VPE
- Microchannel heat exchanger
- Design Code: ASME BPV Code Section VIII Div I
- Core/Nozzle Material: SS 316L
- Design UA=3kW/K
- Design $dP=0.3$MPa
TCES + sCO₂ Power Cycle Transient Modeling

100 MWe Cycle Performance

- Efficiency (%)
- Ambient Temperature (°C)

Ambient temperature (degC)

- Power output (kW)

GT-Suite
Steady-state
TCES + sCO₂ Power Cycle Transient Modeling