Supercritical Carbon Dioxide Pilot Plant Test Facility
DE-FE0028979

Scott Macadam, Gas Technology Institute

2021 UTSR Project Review Meeting
November 9, 2021
Promise of sCO$_2$ Power Cycles

Promise:
> Efficient, Compact, Scalable, low water, low-carbon power generation

Plans to Demonstrate:
> Operability, Turbomachinery, Seals, Heat Exchangers, Durability, Materials, Corrosion, Cost

Versatile Technology – Broad Applicability:

- Concentrated Solar
- Fossil Fuel/Biomass
- Geothermal
- Nuclear
- Energy Storage
- Waste Heat Recovery
Supercritical Transformational Electric Power (STEP) Project DE-FE0028979

Scope: Design, construct, commission, and operate 10 MWe sCO₂ Pilot Test Facility
Reconfigurable to test new technologies in the future

Goal: Advance state of the art for high temperature sCO₂ power cycle performance
Evolve Proof of Concept (TRL3) to operational System Prototype (TRL7)

Schedule: Three budget phases over six years (2016-2023)
Currently in Budget Phase 2 – Fabrication & Construction

Team: U.S. Department of Energy (DOE NETL)
Gas Technology Institute (GTI®)
Southwest Research Institute (SwRI®)
General Electric Global Research (GE-GR)

Industry Partners:
**STEP Project Objectives**

STEP Demo will demonstrate a fully integrated functional electricity generating power plant using transformational sCO₂-based power cycle technology.

- **Demonstrate pathway to efficiency** > 50%
- **Demonstrate cycle operability** >700°C turbine inlet temperature and 10 MWₚ net power generation
- **Quantify performance benefits:**
  - 2-5% point net plant efficiency improvement
  - 3-4% reduction in LCOE
  - Reduced emissions, fuel, and water usage
- **Demonstrate Reconfigurable flexible test facility**
  - Available for Testing future sCO₂ equipment & systems

STEP will be among the largest demonstration facilities for sCO₂ technology in the world.
Simple and Recompression Brayton Cycle test configurations planned to achieve project objectives

**Simple Recuperated Brayton Cycle**

- **Objectives**
  - Demonstrate initial cycle performance with reduced risk configuration
  - Reduced Turbine inlet at 500°C similar to Waste Heat Recovery applications
  - Single compressor configuration
  - Provides Steady & Transient Cycle Performance Data used to predict RCBC performance and operations

**Recompression Brayton Cycle (RCBC)**

- **Objectives**
  - Demonstrate high performance cycle with parallel compressors & multiple HEX
  - Increase Turbine inlet to 715°C
  - Measure Steady & Transient Cycle Performance Data, evaluate operability
  - Demonstrate pathway to 50% thermal efficiency
  - Supports application to in-direct coal, HT WHR Industrial sources, and CSP plants
STEP Project Status

> Site Construction Progress Excellent
  — Building Occupancy received in early June 2020 on schedule
  — Process Electrical, Primary Heater, Cooling Water, Compressor Installation progressing

> Significant Achievements on Major Equipment Design & Fabrication
  — Most Major Equipment delivered or near completion
  — Equipment deliveries to site started in Nov 2019 and new arrivals every month

> Challenges with ‘first of a kind’ equipment
  — High Temperature Recuperator Design Life
  — Fabrication of Turbomachinery, Primary Heater Fabrication, and Turbine Stop Valve
  — Resolved technical issues and progressing with final equipment manufacture and delivery

> Developing supply chain for new materials and large-scale equipment
> Installation of equipment on-going with commissioning starting in Spring 2022
STEP Demo Objectives – Technology Maturation

Advance state of the art for high temperature sCO$_2$ power cycle performance from Proof of Concept to System Prototype validated in an operational system (Technology Readiness Level 3 to 7)
STEP Demo Objectives – Technology Maturation

Advance state of the art for high temperature sCO₂ power cycle performance from Proof of Concept to System Prototype validated in an operational system (Technology Readiness Level 3 to 7)
STEP Demo Objectives – Technology Maturation

Advance state of the art for high temperature sCO\textsubscript{2} power cycle performance from Proof of Concept to System Prototype validated in an operational system (Technology Readiness Level 3 to 7)

INDIRECT-FIRED CYCLE

Materials

Development of compatible materials for high T sCO\textsubscript{2} conditions

Large-scale fabrication of sCO\textsubscript{2} heater coil – welded Inconel 740H tubes

First large-scale complex Inconel 740H tube heat exchanger installed
Heater coil operates at 265 bar and 700°C
STEP Demo Objectives – Technology Maturation

Advance state of the art for high temperature sCO$_2$ power cycle performance from Proof of Concept to System Prototype validated in an operational system (Technology Readiness Level 3 to 7)

Large-scale cast Haynes 282 Turbine Stop Valve design and fabrication

First large-scale complex Haynes 282 Casting Turbine Valve operates at 265 bar and 700°C
Process Equipment Progress

- Blue – Received and Set
- Green – Received
- White – In Fabrication
Timeline to Test Operations

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete Key Equipment deliveries</td>
<td>Jan. 2022</td>
<td></td>
</tr>
<tr>
<td>Complete Commissioning Simple Cycle</td>
<td>Sep. 2022</td>
<td></td>
</tr>
<tr>
<td>Complete RCBC Reconfiguration</td>
<td>Apr. 2023</td>
<td></td>
</tr>
<tr>
<td>Mechanical Completion – Simple Cycle</td>
<td>May 2022</td>
<td></td>
</tr>
<tr>
<td>Complete Simple Cycle Tests</td>
<td>Dec. 2022</td>
<td></td>
</tr>
<tr>
<td>Complete RCBC Tests (End Project)</td>
<td>Dec. 2023</td>
<td></td>
</tr>
</tbody>
</table>

sCO₂ Inventory Storage
Test Facility
sCO₂ Heater
Cooling Towers
Electrical Load Banks
Electrical Power & Back Up Generators
STEP Test System Modeling

<table>
<thead>
<tr>
<th>Steady State</th>
<th>Transient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Software</td>
<td>Aspen Plus, Flownex</td>
</tr>
<tr>
<td>Property Method</td>
<td>NIST REFPROP</td>
</tr>
<tr>
<td>Cases Analyzed</td>
<td>2 Simple Cycle, 7 RCBC</td>
</tr>
<tr>
<td>Purpose</td>
<td>Results used to define equipment requirements and specifications</td>
</tr>
</tbody>
</table>

Data generated will be used to validate the steady state and transient models, which will be used to project performance at the commercial scale and be valuable tools for other sCO₂ systems in the future.
## Steady State Modeling Initial Results

<table>
<thead>
<tr>
<th>Model Names</th>
<th>Cycle Configuration</th>
<th>Description</th>
<th>Load %</th>
<th>Net Power Level (MWe)</th>
<th>Cooler Exit Temperature</th>
<th>Turbine Inlet Temperature</th>
<th>Cycle Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>133</td>
<td>Simple</td>
<td>Simple cycle minimum load case</td>
<td>Min</td>
<td>2.5</td>
<td>35°C</td>
<td>500°C</td>
<td>22.6%</td>
</tr>
<tr>
<td>136</td>
<td>Simple</td>
<td>Simple cycle maximum load case</td>
<td>Max</td>
<td>6.4</td>
<td>35°C</td>
<td>500°C</td>
<td>28.3%</td>
</tr>
<tr>
<td>151</td>
<td>Recompression</td>
<td>Baseline case</td>
<td>100%</td>
<td>10.0</td>
<td>35°C</td>
<td>715°C</td>
<td>43.4%</td>
</tr>
<tr>
<td>152</td>
<td>Recompression</td>
<td>“Hot” Day Case</td>
<td>70%</td>
<td>6.6</td>
<td>50°C</td>
<td>675°C</td>
<td>37.4%</td>
</tr>
<tr>
<td>153</td>
<td>Recompression</td>
<td>“Cold” Day Case</td>
<td>100%</td>
<td>9.9</td>
<td>20°C</td>
<td>525°C</td>
<td>36.8%</td>
</tr>
<tr>
<td>154</td>
<td>Recompression</td>
<td>Partial load case using inventory control</td>
<td>40%</td>
<td>4.0</td>
<td>35°C</td>
<td>715°C</td>
<td>37.0%</td>
</tr>
<tr>
<td>155</td>
<td>Recompression</td>
<td>RCBC at 500°C turbine inlet temperature</td>
<td>70%</td>
<td>6.9</td>
<td>35°C</td>
<td>500°C</td>
<td>32.5%</td>
</tr>
<tr>
<td>157</td>
<td>Recompression</td>
<td>Partial load case using TSV throttling (transient condition)</td>
<td>40%</td>
<td>4.2</td>
<td>35°C</td>
<td>715°C</td>
<td>30.8%</td>
</tr>
<tr>
<td>157a</td>
<td>Recompression</td>
<td>Partial load case using TSV throttling</td>
<td>40%</td>
<td>3.9</td>
<td>35°C</td>
<td>675°C</td>
<td>29.6%</td>
</tr>
</tbody>
</table>
Simple Cycle Power Level Transient Sample Results

➢ Max Load (6.4 MWe) → Min Load (2.5 MWe) → Max Load (6.4 MWe) by throttling the Turbine Stop Valve (TSV)

➢ TSV (gray line) closes to 17% open at 200s and reopens fully at 1500 seconds
➢ As a result:
   ➢ The HTR bypass valve (purple triangle) opens to maintain a 7°C approach temperature to protect the HTR
   ➢ The 3-way valve of the cooler (red and yellow lines) adjusts flow through and around the cooler to maintain a 35°C inlet temperature to the MC
   ➢ The ASV opens slightly to allow minimal recycle
Transient Modeling Key Findings

- Control valve schedules during start-up were evaluated and determined.
- Sequence approaches to manage component temperatures within specification.
- Determined timing to enable heater ignition/firing at minimum system flowrate.
- Determined if liquid formation occurs during loop filling.
- Determined start up and interactions of two parallel compressor loops for RCBC.
- Evaluated fast ramp scenarios and identified limiting capabilities of other sub-systems.
A virtual simulator will be built of the facility.

Flownex will represent the hardware physics.

Mark VI controller will be used for the virtual controller.

Operators will use this simulator:
- Training to gain familiarity with test system dynamics
- Practice various control strategies
- Assess “What if” scenarios
Summary & Conclusions

- Facility Significant Progress on Major Equipment Fab/Installation

- Challenges with low TRL equipment which is educating the industry engineers and supply chain
  - Turbomachinery, High Temperature Recuperator, Primary Heater, and Turbine Stop Valve

- Commissioning to Initiate in Spring 2022

- Modeling of System Operation in Simple and RCBC configurations completed
  - Continue to Anchor Model to Commissioning and Simple Cycle/RCBC Test Data

- Digital Simulator using those System Models being developed to train operators and potential commercial system developers

- STEP Project Status can be followed at www.STEPdemo.us
Gratefully Acknowledging the Support from U.S. DOE-NETL and Project Partners

This presentation was prepared by GTI as an account of work sponsored by an agency of the United States Government. Neither GTI, the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors herein do not necessarily state or reflect those of the United States Government or any agency thereof.