STEP Project Overview
sCO2 Transformational Electric Power

Presented to European Turbine Network

Date Held: February 25, 2021

STEP Project Management Presentation Agenda

- Introductions — Markus Lesemann
- Project Overview & Status — Brian Lariviere
- Facility and Test System Description — Aaron McClung
- Commissioning, Start Up, and Test Plan
- Industry Partnership and Q&A — Brian Lariviere

Project Execution Organization

Don Stevenson (GTI)
John Marion (GTI)
Tim Allison (SwRI)
Darren Hallman (GE-GR)

Project Steering Committee
- DOE
- Project team (GTI, SwRI, GE)
- JIP (Joint Industry Program) Cost-sharing organizations (national & international)

Project guidance/ recommendations

National Energy Technology Laboratory
Project Coordination
Seth Lawson
Program Manager

KEPCO · Natural Resources Canada / Ressources naturelles Canada · American Electric Power · Southern Company · ENGIE · CSIRO · EGAT Power for Thai Happiness

STEP Project Team

SwRI — Aaron McClung, Program Manager

gti — Brian Lariviere, Program Director

GE — Jason Mortzheim, Program Manager

Co-PI's for Project Execution with GTI lead

Texas Commission on Environmental Quality · University of Houston, Cullen College of Engineering

Natural Resources Canada / Ressources naturelles Canada

University of Wisconsin-Madison

Supercritical Transformational Electric Power (STEP) Project DE-FE0028979

Scope: Design, construct, commission, and operate **10 MWe sCO_2 Pilot Test Facility**
Reconfigurable to test new technologies in the future

Goal: Advance state of the art for high temperature sCO_2 power cycle performance
Evolve Proof of Concept (TRL3) to operational System Prototype (TRL7)

Schedule: Three budget phases over six years (2016-2022)
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 Program 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%**

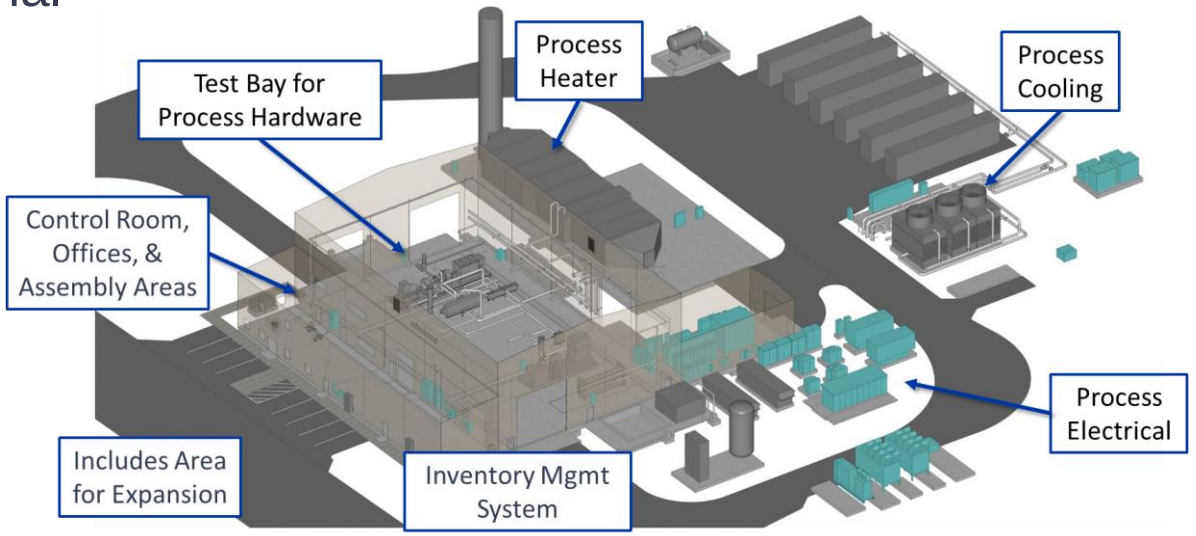
Demonstrate cycle operability **>700°C** turbine inlet temperature and 10 MWe net power generation

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

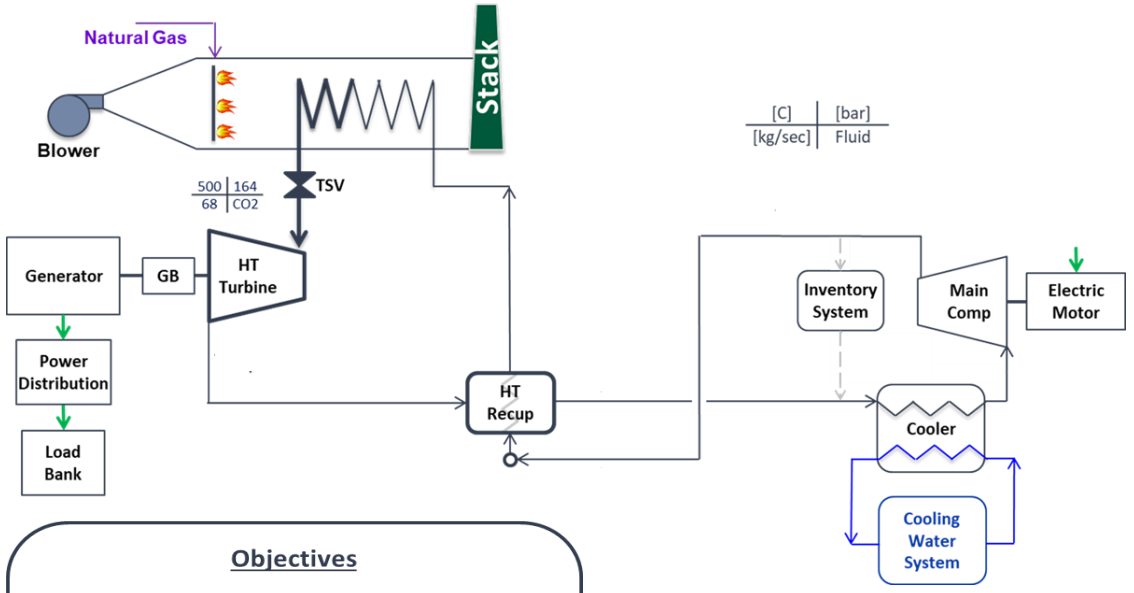
- Available for Testing future sCO2 equipment & systems



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

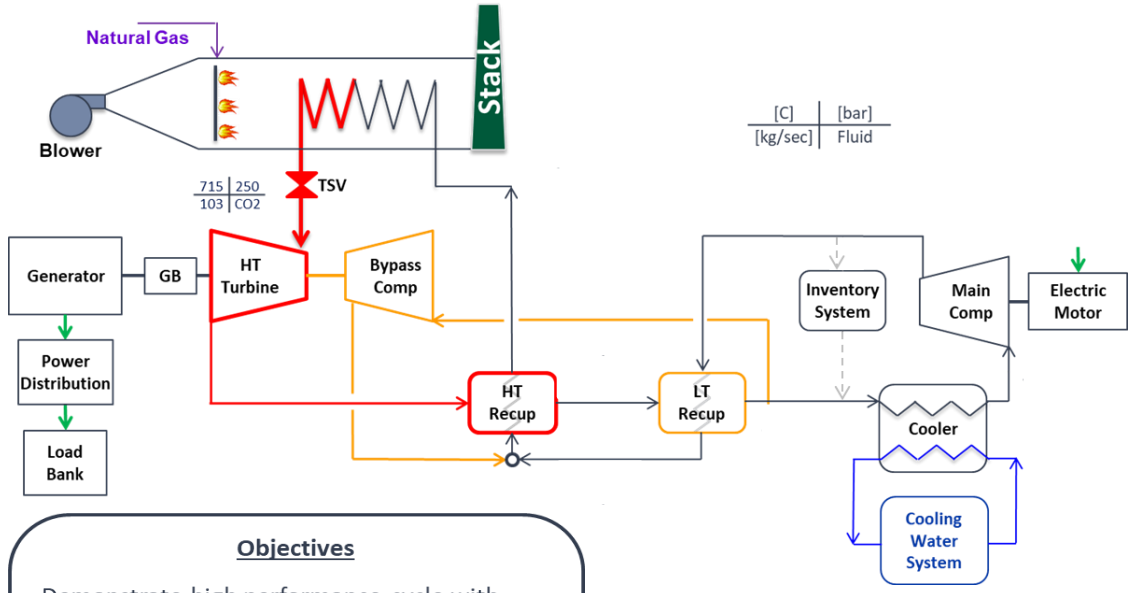


Objectives

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

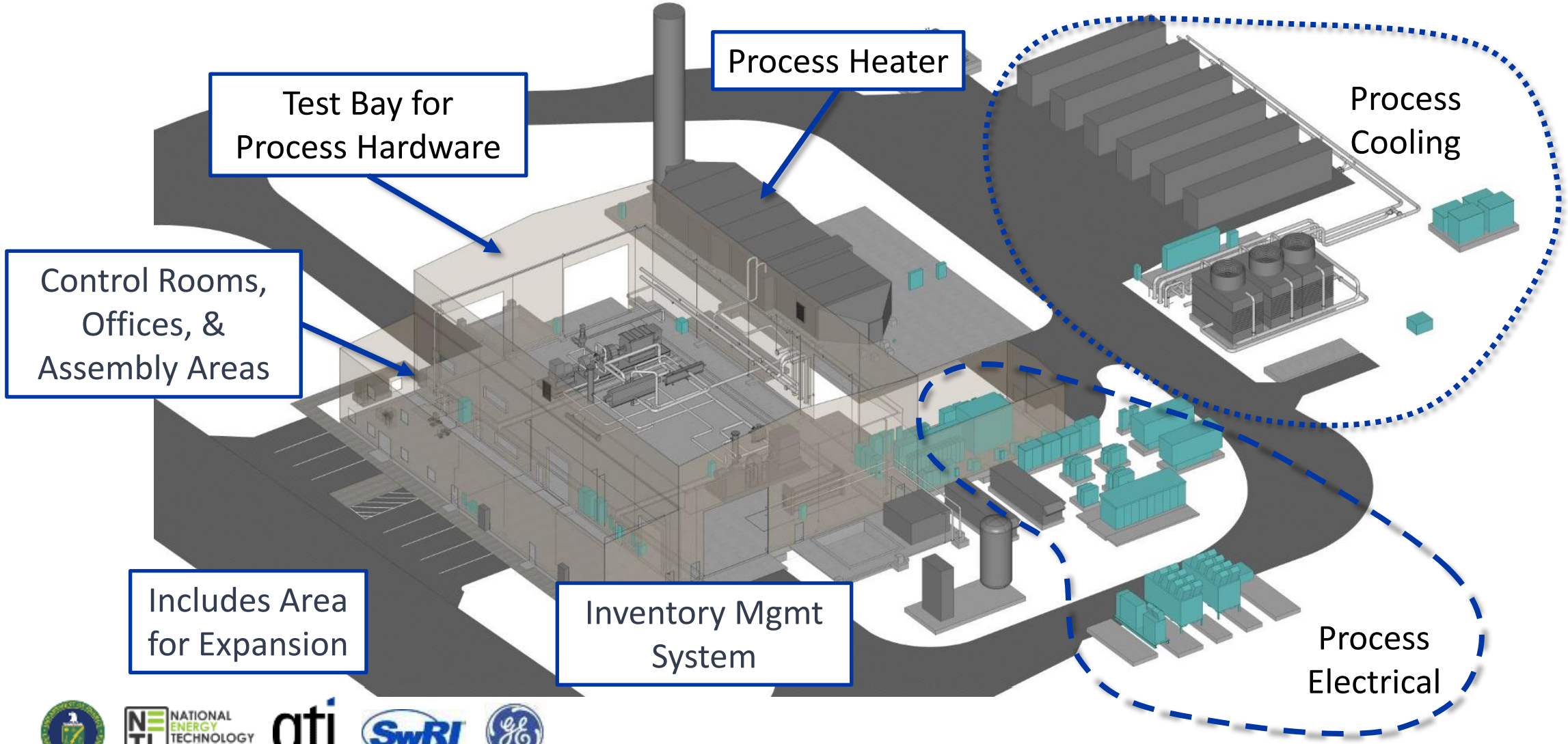
Demonstrate high performance cycle with parallel compressors & multiple HEX

- 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

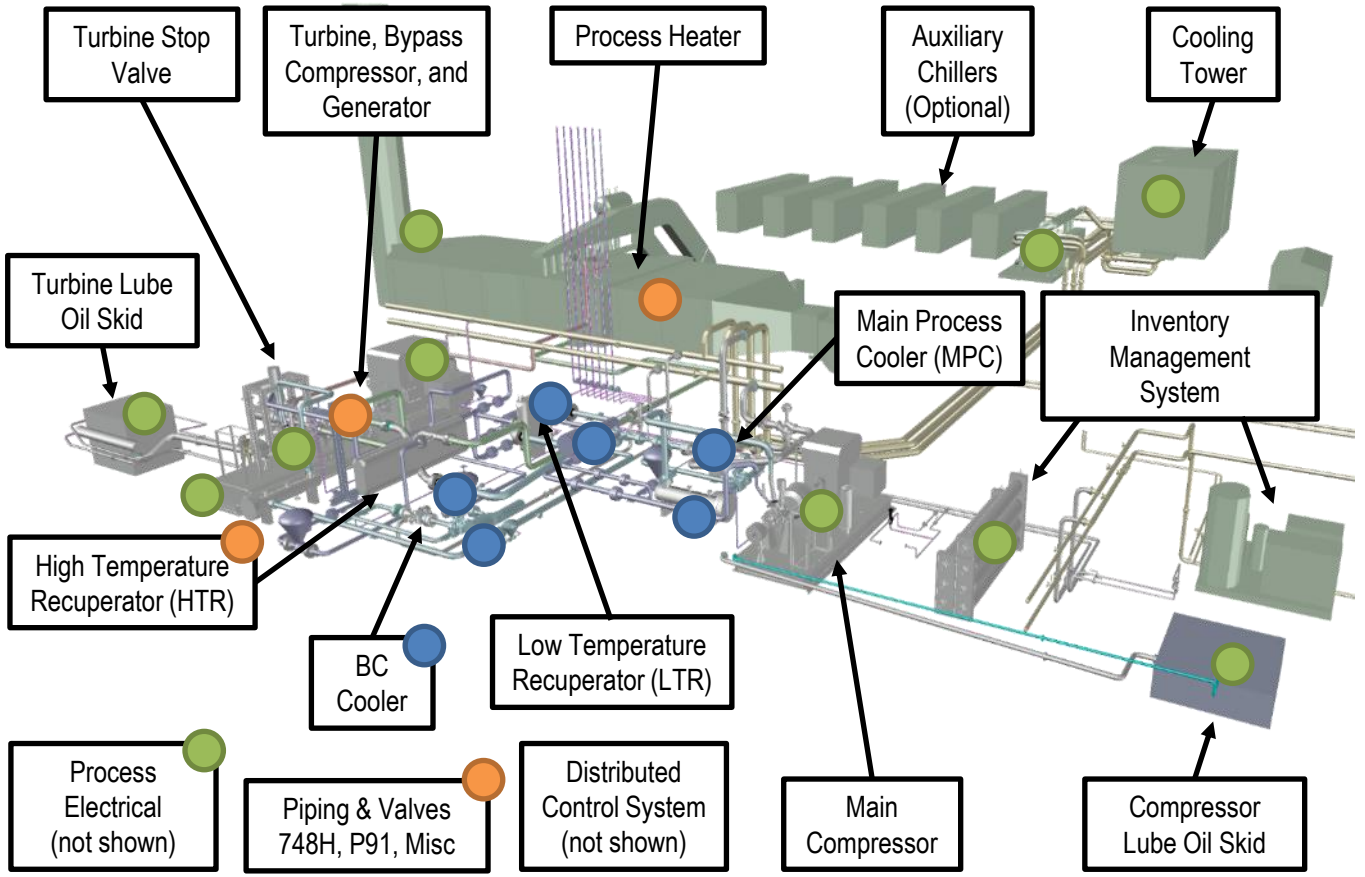
STEP Project Status

- **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 impacted schedule**
  - Turbomachinery, High Temperature Recuperator, Primary Heater, and Turbine Stop Valve
  - Resolved technical issues and progressing with final equipment manufacture and delivery
- **Industry investment received during COVID pandemic**
  - 3 new members

STEP - Flexible Test Facility

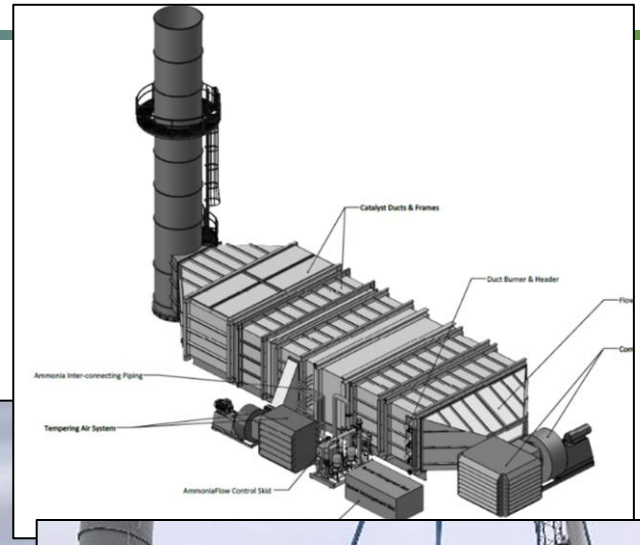


Facility Construction Completed at Test Site in San Antonio, TX



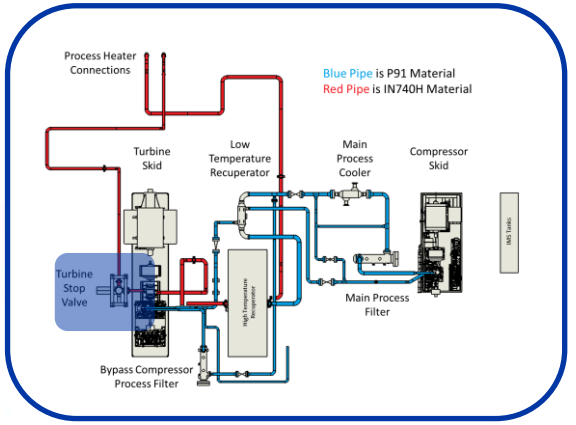
Process Heater construction on going

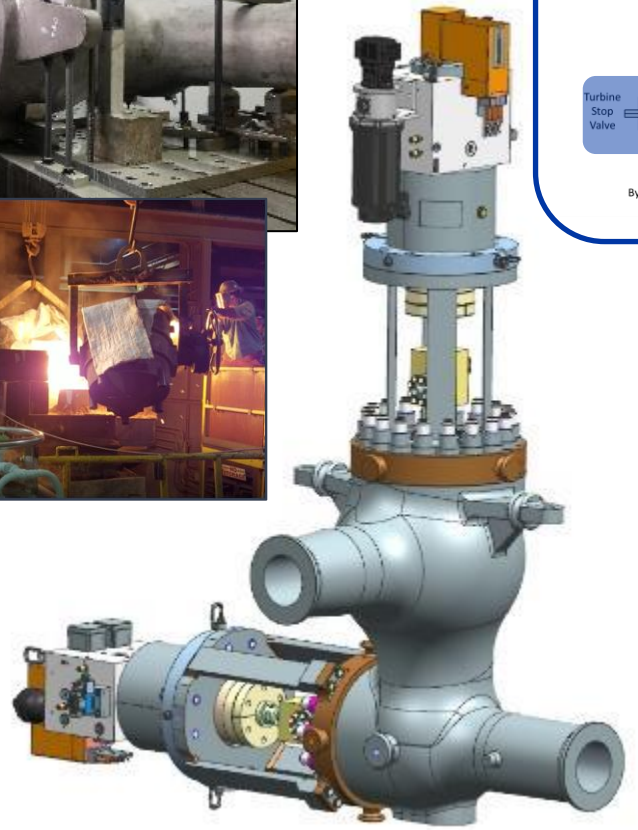
- Heat Recovery Steam Gen (HRSG) style “boiler”
  - Duct NG burner ~ 50 MWth
  - Designed to ASME BPV Section 1
  - Size: 14’W x 133’L x 18’H
- Optimus Industries, LLC



STEP Turbine Stop/Control Valve (TSV)

- Turbine Control and Stop Function
  - Provided by GE Power
  - Based on conventional steam valves with sCO2 specific features
  - Leverages Haynes 282 material development under DOE AUSC program
  - Stem Seal Design Tests Completed
  - **First production Haynes 282 Valve**

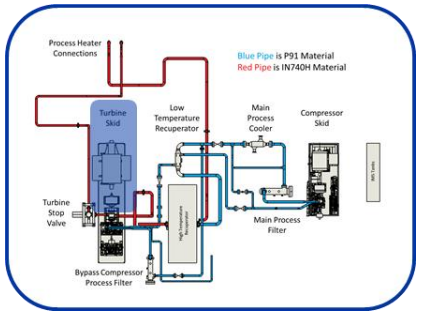


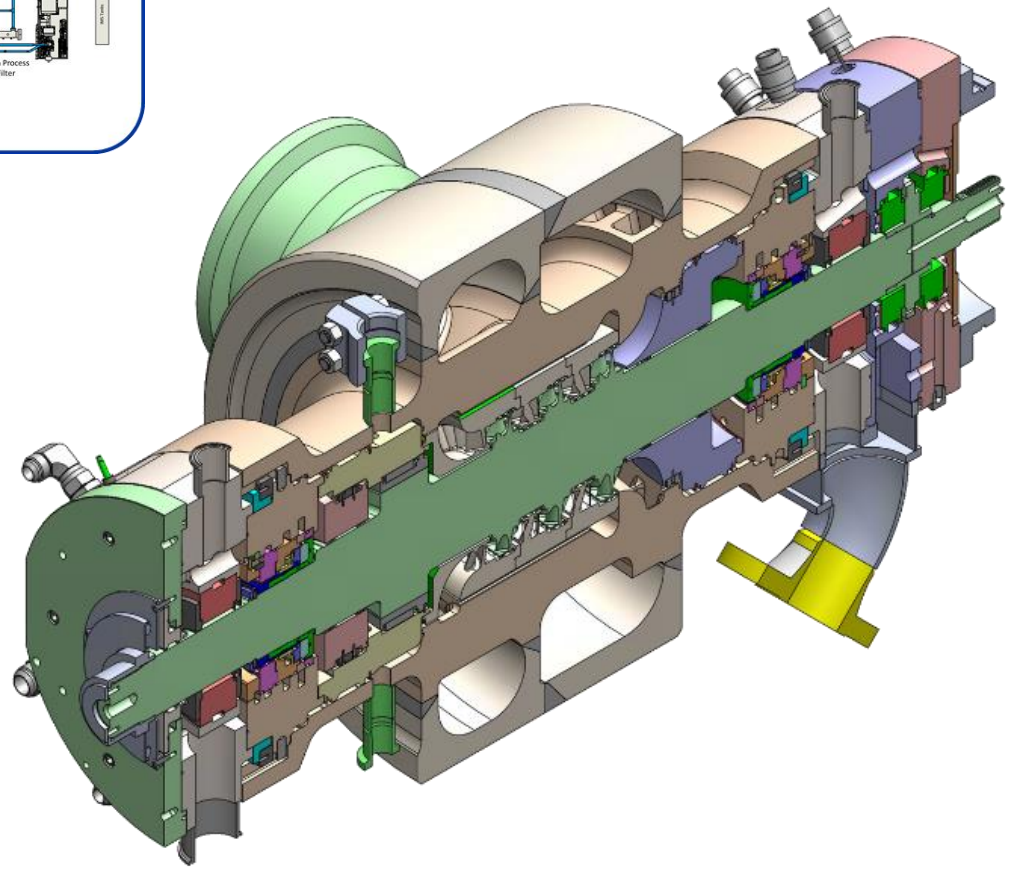


Testing Completed On sCO2 Stem Seals

STEP Turbine - Builds on SunShot success

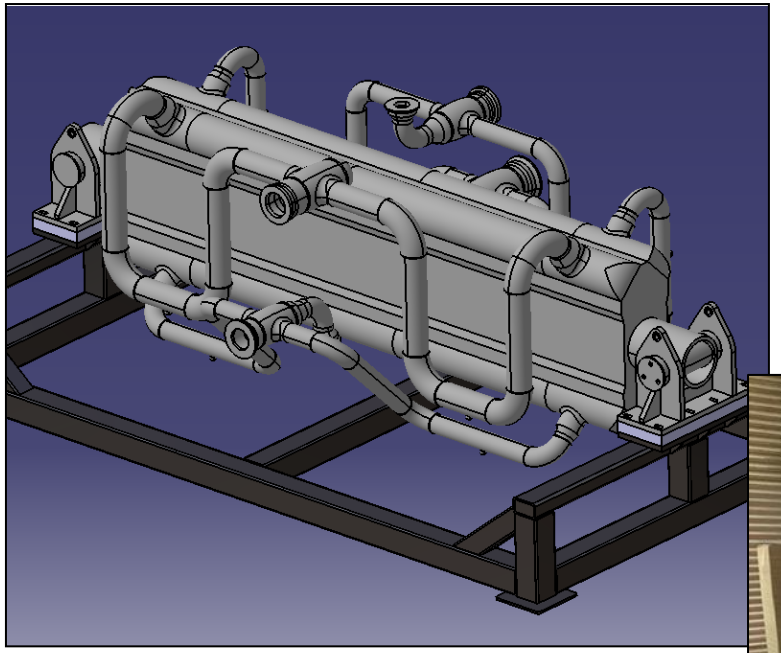
- Collaboration between GE-RC and SwRI
- Design challenges include high blade loading and large temperature gradients
- Based on frame design demonstrated under the EERE SunShot program
- **Incorporates updated flowpath for higher performance**
- **Revised casing design incorporates lessons learned from EERE SunShot**
- **Fabrication of components on going**

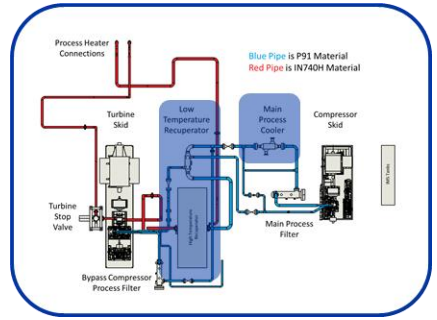




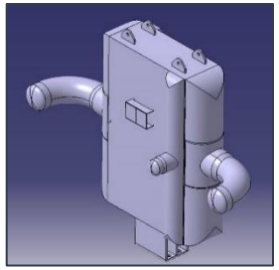
High Temp Recuperator fabrication continues

- HTR (High Temp Recuperator)
  - sCO2/sCO2 service
  - 49 MWth duty, 600ºC design temp
- Heatric, Inc.
  - PCHE Fabrication
  - Design life/structural issues delayed fabrication
  - Design Completed, Material Ordered
  - All HEX Cores Fabricated & Bonded
- Delivery Planned for August 2021

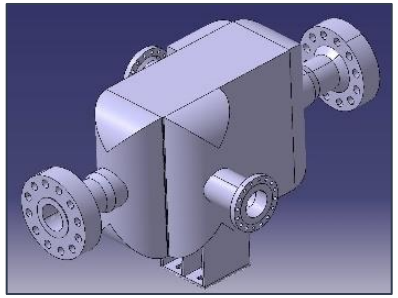




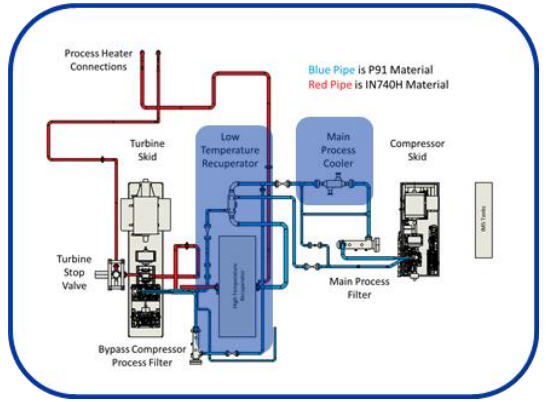
All Low Temperature Recuperators and Coolers delivered awaiting installation at SwRI



Low Temp Recuperator
13 MWth duty @ 250°C



Main Process Cooler
16MWt duty @ 150°C



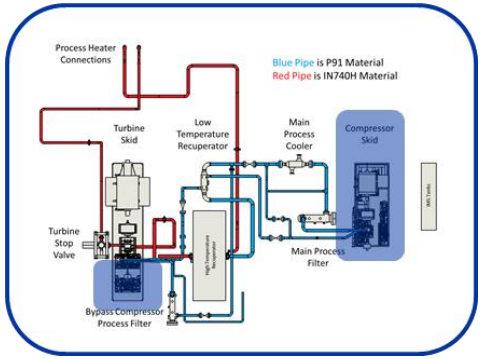
Low Temperature Recuperator
Heatric, Inc.

Main Process Cooler
Heatric, Inc.

Bypass Cooler
VPE

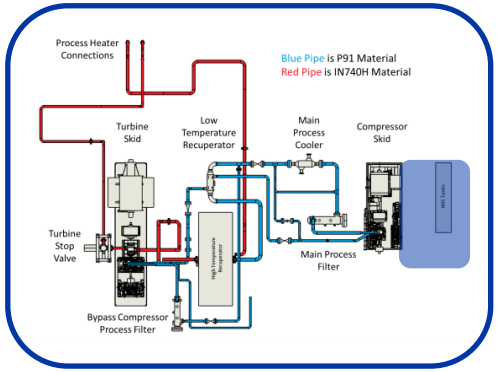
STEP Compressor Systems Delivered and Set

- Main Compressor driven by electric motor
- Bypass Compressor directly driven by STEP sCO2 turbine
- Baker-Hughes OEM of Main & Bypass Compressors
  - Design based on industrial CO2 compressors and DOE Apollo project DE-EE-0007109



Inventory Management System

- Dual functions
  - Manage system inventory
  - Provide for initial system fill and makeup
- System control
  - System inventory along with Heat Rate and Compressor IGVs influence overall system Pressure Ratio and Mass Flow (Power Output)
  - Optimal system control leverages inventory control to operate at peak thermodynamic efficiency across the load range
- Fill and Makeup
  - Supporting auxiliary supply flows for Dry Gas Seal supply, Turbine Stop Valve Stem Seals
  - Replenish inventory vented to atmosphere
- Status of the IMS System
  - Long lead equipment procurement is complete, working through short lead piping and valves



System Includes:

- Storage Tank
- Bulk Liquid Tanks
- Liquid Pumps
- Vaporizers
- Cooling/Heating

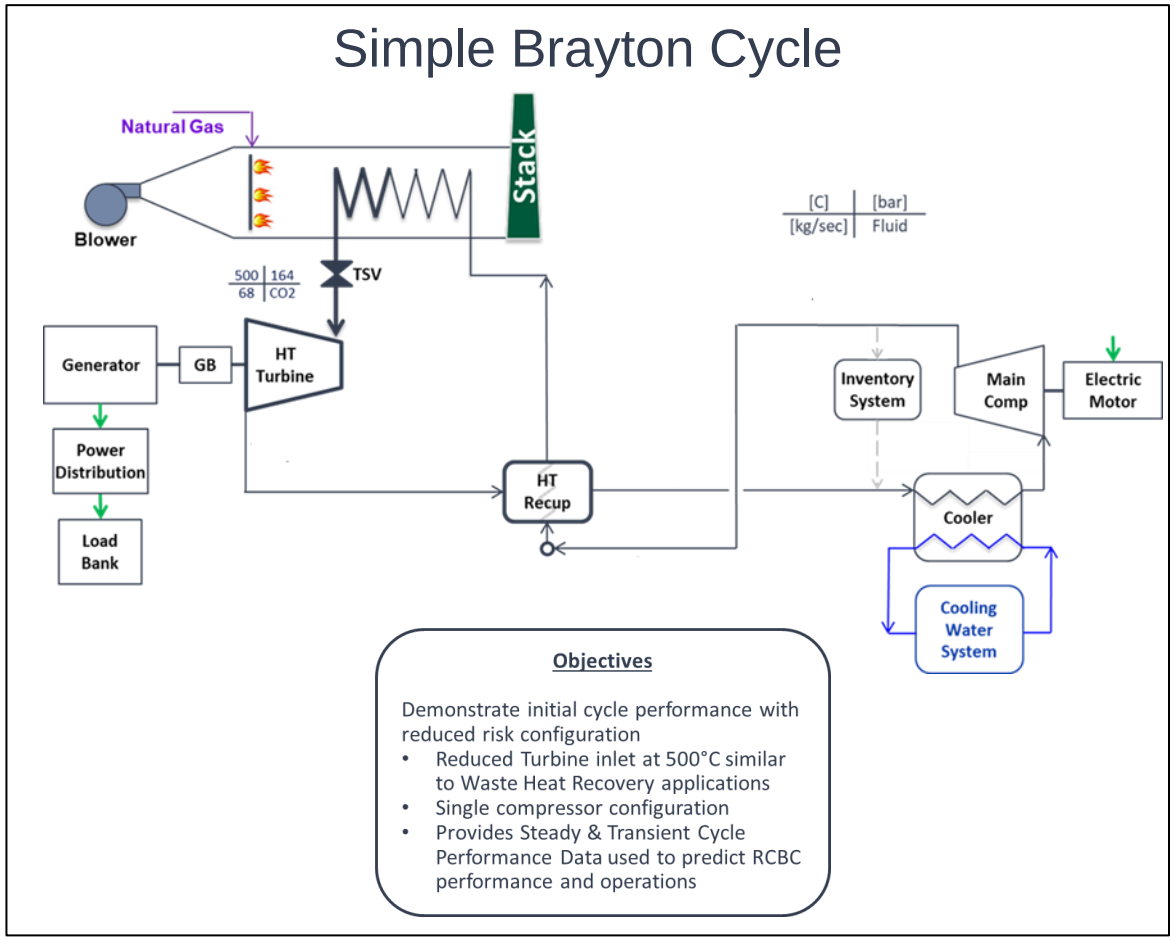
Simple Cycle Test Objectives Per SOPO

STEP DEMO

> Objectives:

- Demonstrate basic operation and control of a simple recuperated sCO2 Brayton power cycle producing greater than 5 MWe.
- Implement and test an automated control system for the safe and predictable operation of the simple recuperated Brayton cycle through normal operating transients and simulated emergency transients.
- Obtain component performance data for sCO2 expander, recuperator, heat source, and compressor over a range of operating conditions to validate component performance predictions.
- Obtain cycle performance data to validate steady state and dynamic models and performance predictions.

This (simple cycle test) plan will verify the facility and component performance at lower temperatures (500°C) and in a configuration with reduced technical risk.



Recompression Closed Brayton Cycle (RCBC) Test Objectives Per SOPO

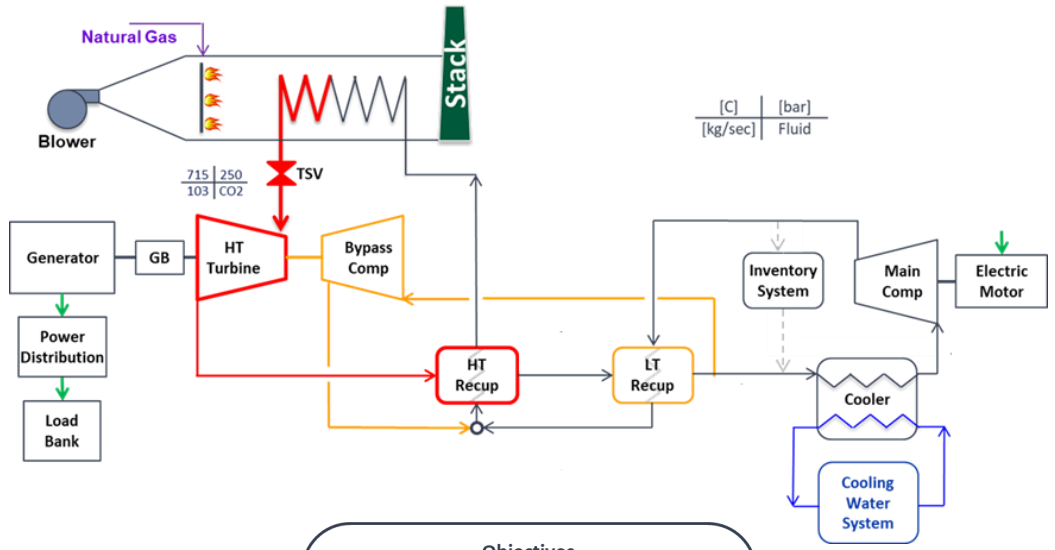
STEP DEMO

> Objectives:

- Demonstrate basic operation and control of a RCBC power cycle producing 10 MWe.
- Implement and test an automated control system for the safe and predictable operation of the RCBC through normal operating transients and simulated emergency transients.
- Obtain component performance data for new and updated components over a range of operating conditions to validate component performance predictions.
- Obtain cycle performance data to validate steady state and dynamic models and performance predictions.

This (RCBC) plan will verify the performance capability of the technology temperatures (715°C) and in a configuration with reduced technical risk.

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

- **Excellent Team with the right experience in sCO2 system design & operations**
- **Site Construction Progress Excellent -** Building Occupancy received on schedule
- **Significant Progress on Major Equipment Fab/Installation**
- **Challenges with low TRL equipment impacted schedule**
  - Turbomachinery, High Temperature Recuperator, Primary Heater, and Turbine Stop Valve
  - Resolved technical issues and progressing with final equipment manufacture and delivery

- **Commissioning to Initiate in early 2021**

- **Industry interest and investment received but more needed to complete project**

- **STEP Project Status can be followed at *www.STEPdemo.us***

STEP Joint Industry Program

STEP is an open project that seeks to benefit the sCO2 community also through a Joint Industry Program.

Industry participation is central to steering project activities.

Two levels of participation:

1. Steering Committee
   - Input and advisory recommendations to the project team
   - Direct participation in bi-monthly advisory meetings
   - Attendance at bi-annual technical interchange meetings
   - Receipt of quarterly technical status reports
   - Real time access and use of Project System Data
   - Opportunity for facility visits and training in system operations
   - Period of exclusive access to license system IP
2. Associate Membership
   - Attendance at bi-annual technical interchange meetings
   - Receipt of quarterly technical status reports
   - Opportunity for 2 site visits per year

For more information on opportunities to participate: www.stepdemo.us

Questions?

Contact:
Markus Lesemann
Director, Business Development
mlesemann@gti.energy
+1 (919) 599 4096