10 MWe Supercritical Carbon Dioxide (sCO_2) Pilot Power Plant

Abstract

Supercritical CO_2 cycles are a promising power generation technology that offers numerous benefits in a range of power applications that include fossil, waste heat, solar, marine, biomass, and nuclear. A team led by Gas Technology Institute (GTI), Southwest Research Institute (SwRI) and General Electric Global Research (GE) has initiated a project to design, construct, commission, and operate a versatile and reconfigurable 10 MWe Supercritical Carbon Dioxide (sCO_2) Pilot Plant Test Facility located at SwRI's San Antonio, Texas campus. The project called STEP Demo (Supercritical Transformational Electric Power) is one of the largest scale and most comprehensive in the world. A key project goal is to advance the state-of-the-art for high temperature sCO_2 power cycle performance from Proof of Concept (Technology Readiness Level [TRL] 3) to System Prototype validated in an operational system (Technology Readiness Level [TRL] 7). The United States Department of Energy (U.S. DOE) has awarded $84 million for this $119 million project, while cost share is provided by the team, component suppliers and other stakeholders interested in sCO_2 technology.

Introduction

The unique properties of supercritical CO_2 offer intrinsic benefits over steam as a working fluid in closed cycles to absorb thermal energy, to be compressed, and to impart momentum to a turbine.
The temperature and pressure threshold conditions required for the supercritical state of CO_2 are nominally 31°C and 7.4 MPa. These conditions are easily achieved, and above these conditions is a supercritical fluid with higher density and incompressibility as compared to steam or air which results in much smaller turbomachinery (factor 10:1) for a given energy production level. Thus, sCO_2 power cycles can offer several benefits:

- Higher cycle efficiencies due to the unique thermodynamic properties of sCO_2
- Reduced emissions resulting from lower fuel usage
- Compact turbomachinery, resulting in lower capex, reduced plant size/footprint, and more rapid response to load transients
- Reduced water usage, including water-free capability in dry-cooling applications
- Heat source flexibility

These benefits can be achieved in a wide range of power applications including gas- and coal-fired power plants, bottoming cycles, industrial waste heat recovery, concentrated solar power, shipboard propulsion, biomass power plants, geothermal power, and nuclear power. Some of these applications are shown in Figure 1 which maps the sCO_2 application space relative to incumbent steam and Organic Rankine Cycle (ORC) options as a function of power output and heat source temperature.

This is a new high-potential technology under development. Demonstrations to date have been limited to laboratory-scale test loops under 1 MWe. To facilitate the development and commercial deployment of the technology, pilot-scale testing is required to validate both component and system performance under realistic cycle conditions at sufficient scale. The STEP Demo is a significant scale-up (to 10 MWe) of a fully integrated and functional electric power plant. Several technical risks and challenges will be mitigated in this project:

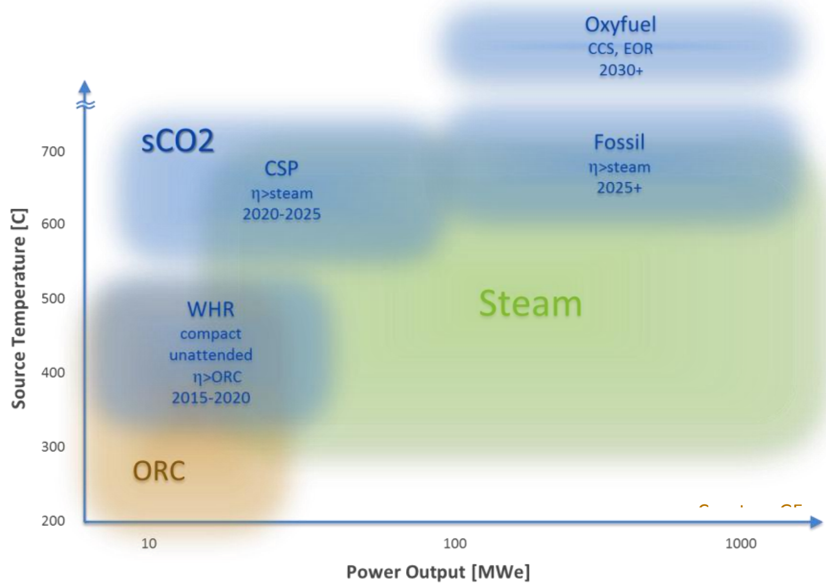


Figure 1. sCO_2 Application Map

- Turbomachinery (aerodynamics, seals, durability)
- Recuperators (design, size, fabrication, durability)
- Materials (corrosion, creep, fatigue)
- System integration and operability (startup, transients, load following)

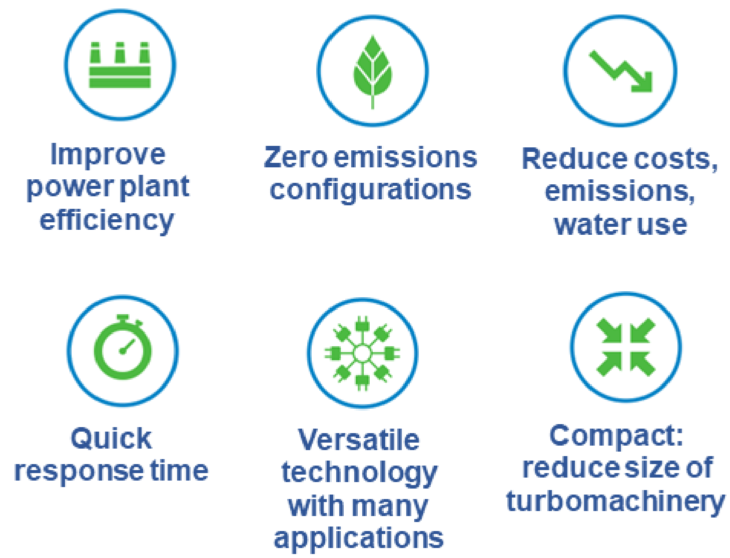
The STEP Demo will advance the state of the art for high temperature sCO_2 power cycle performance from Proof of Concept (TRL 3) to System Prototype validated in an operational system (TRL 7).

Objectives

The project has several key objectives:

- Demonstrate the operability of the indirect sCO_2 power cycle
- Verify the performance of components (turbomachinery, recuperators, and compressors, etc.)
- Show the potential for producing a lower cost of electricity and the potential for a thermodynamic cycle efficiency greater than 50% at commercial scales.
- Demonstrate at least a 700°C turbine inlet temperature and a Recompression Closed Brayton Cycle (RCBC) configuration that demonstrates system and component design and performance, including generating at least 10 MWe
- Reconfigurable facility to accommodate future testing
  - System/cycle upgrades
  - New cycle configurations (i.e., cascade cycles, directly fired cycles, etc.)
  - New or upgraded components (turbomachinery, recuperators and heat exchangers)

Project Organization and Scope



GTI, SwRI, and GE have formed a team to direct all STEP Demo project technical activities in line with program goals and objectives. GTI is responsible for overall management of the project and for communication with DOE. GTI is currently performing technology management, systems engineering and integration, major component procurements and will participate in testing in a test management role. SwRI will provide the host site for the test facility. They are performing the facility design engineering and will construct the test facility, including the utility infrastructure. SwRI will perform facility commissioning as well as direct and execute test operations. GE Global Research (GE) is providing the technical definition for the turbomachinery (turbines and compressors) as well as a first-of-a-kind sCO_2 turbine stop/control valve based on their line of valves for high-pressure steam turbines.

The combined team integrates the strengths of each individual organization and in aggregate, have completed or performing over two dozen sCO2 technology related project forming the building blocks for a successful STEP Demo. GTI has proven leadership in large pilot/facility projects including joint government/industry/international partnerships. SwRI offers technology development and test operations experience on-site at the chosen San Antonio, TX test site. GE leverages their experience and existing 1 MWe turbomachinery component hardware developed for DOE SunShot program to reduce program risk.

The team has developed a phased testing approach to successively mitigate risks.

The testing will occur in two distinct phases as shown in Figures 2a and 2b. The initial system configuration will be the sCO_2 Simple Cycle which comprises a single compressor, turbine, recuperator, and cooler. Heat will be supplied by a natural-gas fired heater that closely resembles a duct-fired Heat Recovery Steam Generator (HRSG). In Simple Cycle testing, sCO_2 will be delivered to the turbine at approximately 500°C and 250 bar. This test configuration offers the shortest time to steady-state and transient data, while demonstrating controls and operability of the system, and performance validation of key components. In the second phase of testing, the system will be reconfigured to the Recompression Closed Brayton Cycle (RCBC). This is a high-efficiency cycle capable of achieving the >50% thermodynamic efficiency goals of the program. In this phase, a second (lower-temperature) recuperator and a bypass compressor will be installed. The turbine inlet temperature will be increased to the target level of 715°C. This phased testing approach will address specific technical risks while minimizing added complexity at each phase. In this manner, programmatic risk can be minimized by reducing unnecessary complexity and applying lessons learned from prior phases to address technical challenges.

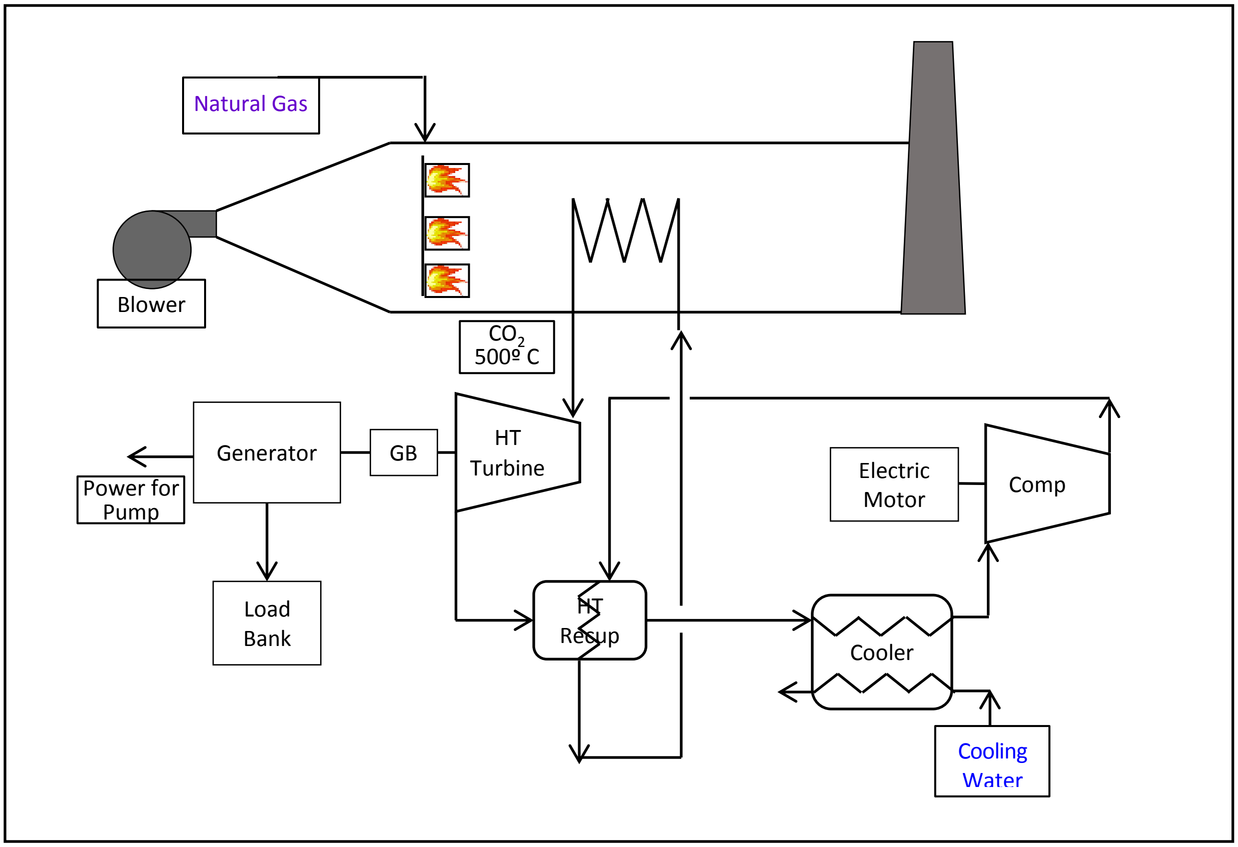


Figure 2a. Simple Cycle Configuration

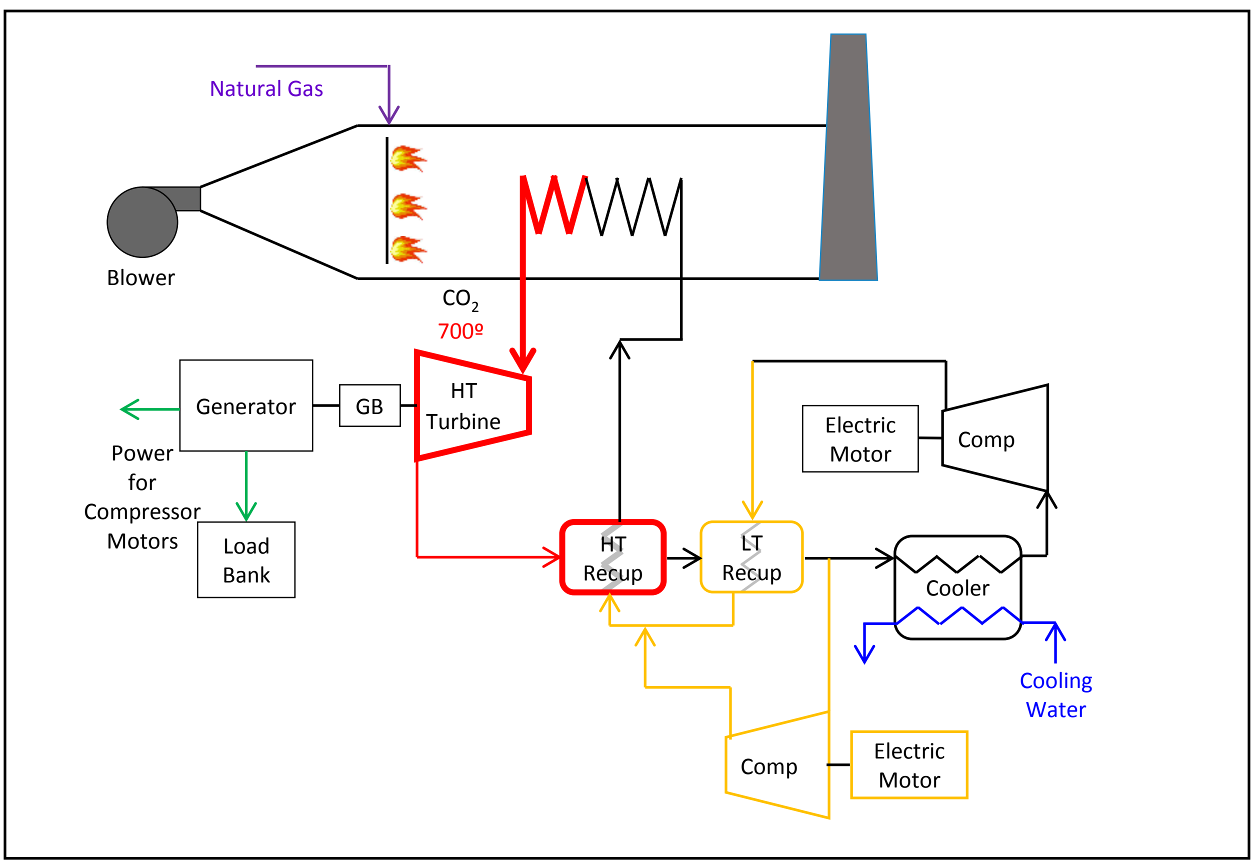


Figure 2b. Recompression Closed Brayton Cycle

Schedule

The STEP project was officially launched in March 2017, and is a six-year effort with three distinct budget periods.

BUDGET PERIOD 1 (ENDS OCTOBER 2018)
Detailed Facility and Equipment Design (25 months)

- System analysis, P&IDs, Component Specs
- Design major equipment
- Procure heat source, cooling tower and long-lead items
- Materials and seal tests
- Start site construction

BUDGET PERIOD 2 (ENDS JANUARY 2021)
Fabrication and Construction (27 months)

- Complete site construction and civil works
- Fabrication and installation of major equipment
- Commissioning and simple-cycle test

BUDGET PERIOD 3 (ENDS SEPTEMBER 2022)
Facility Operation and Testing (20 months)

- Facility reconfiguration
- Test recompression cycle

Project Status

Technology Development Tasks

The project includes several technology development tasks involving the turbine, turbine stop valve, and materials testing. A conceptual schematic of the 14 MWe (gross) sCO_2 turbine, jointly designed by SwRI and GE, is shown in Figure 3. This effort leverages an existing U.S. DOE-funded SunShot program in which SwRI and GE have fabricated and are currently testing a similar turbine. This turbine is also designed for a turbine inlet temperature of 700°C but will be operated at reduced flow conditions, limiting power output to 1 MWe.

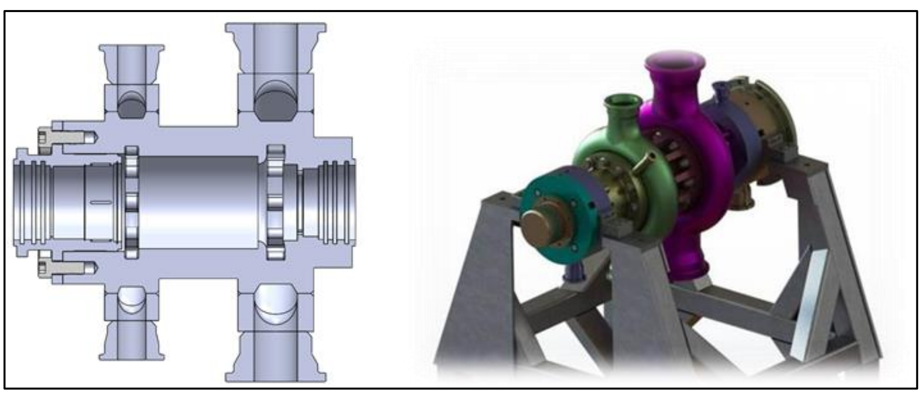


Figure 3. Conceptual design of 14 MWe STEP sCO_2 turbine Configuration

The STEP turbine will offer improvements over the SunShot turbine, including: increased casing and rotor life (100,000 hrs vs 20,000 hrs), shear ring retention rather than bolts, a design for couplings on both shaft ends, and improved aero performance with increased volute flow area. Also, upgrades to hot gas seals and thermal management local to seals will be implemented based upon lessons learned from the SunShot effort and related supporting projects. Current STEP turbine design activities are focused on torsional train dynamics, rotor flowpath preliminary design; and flowpath mechanical and aeromechanical integrity.

GE is also leading the design of the turbine control/stop valve which will be placed upstream of the turbine. The design is based on the existing commercial product line of steam valves, but with modifications to accommodate sCO_2 fluid and high operating temperatures, including novel stem seal materials.

Facility Design

SwRI is leading the facility design efforts. The facility is at a greenfield site on their campus in San Antonio, Texas.

SwRI has completed the building layout and general arrangement plan (Figures 4 and 5), along with initial analyses of the interconnecting piping system. The Environmental Assessment was completed by an external specialist vendor and has been approved by the DOE. Groundbreaking took place in October 2018.

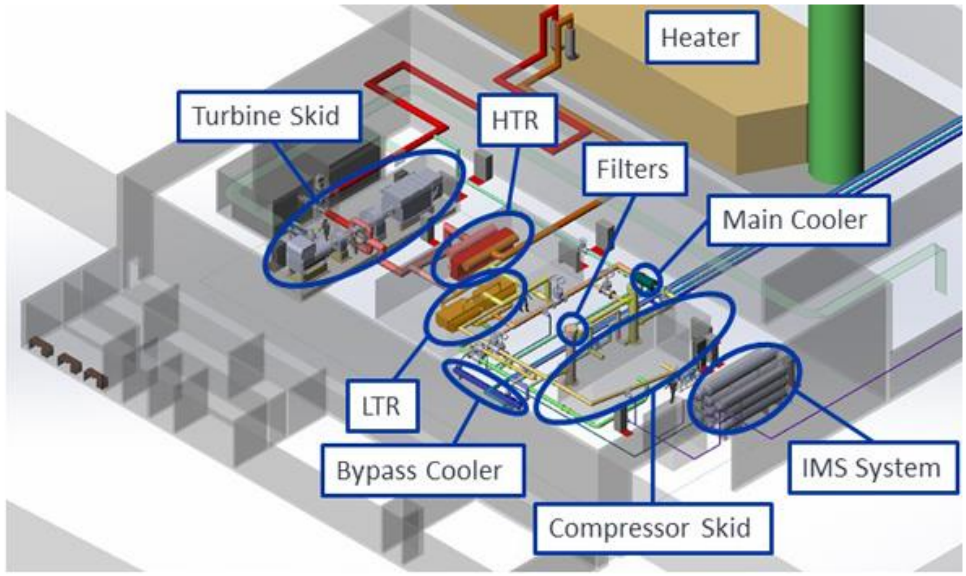


Figure 4. Equipment layout of STEP facility

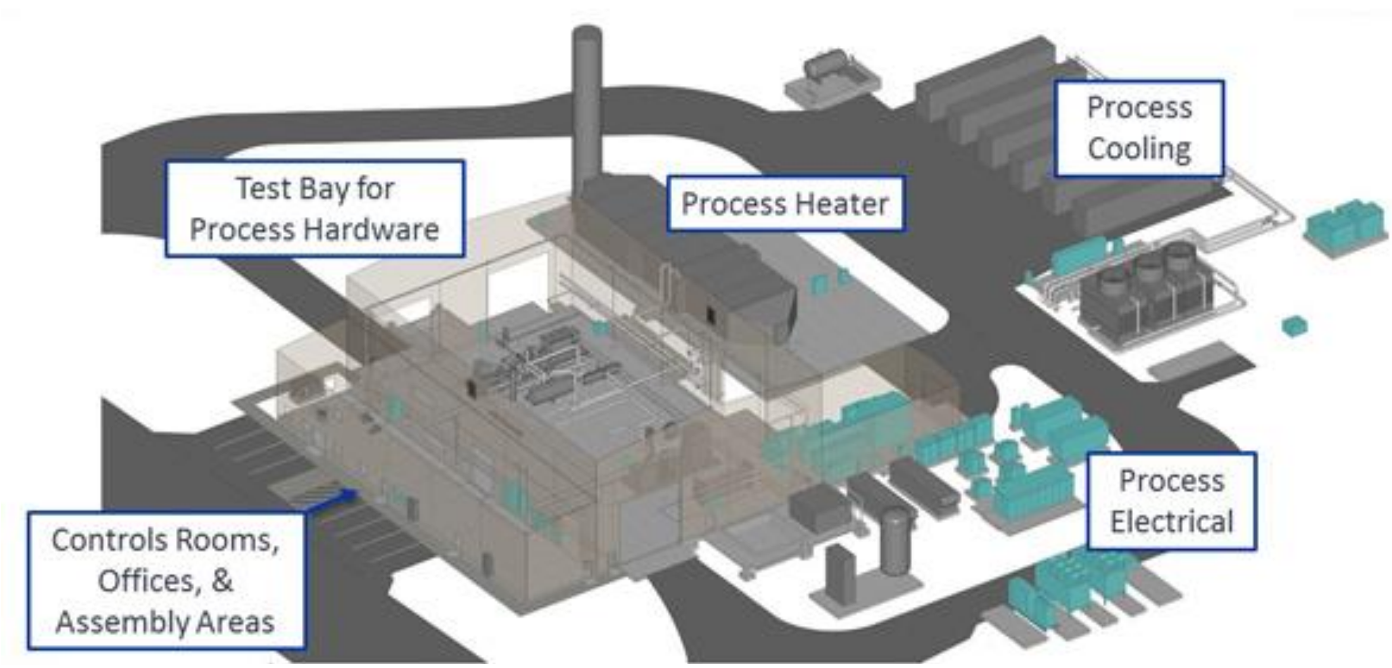


Figure 5. Renderings of facility exterior and interior

Other Key Components

GTI has completed a steady-state modeling study of all design and off-design cases, for both Simple Cycle and RCBC testing. Information from this study has been used to develop specifications for key components. In addition, development of a transient model is underway. The objective is to develop a tool to simulate start-up, trip, shut-down and transient cases. The STEP Demo will validate steady-state and transient models critical for operations and for future commercial design and controls.

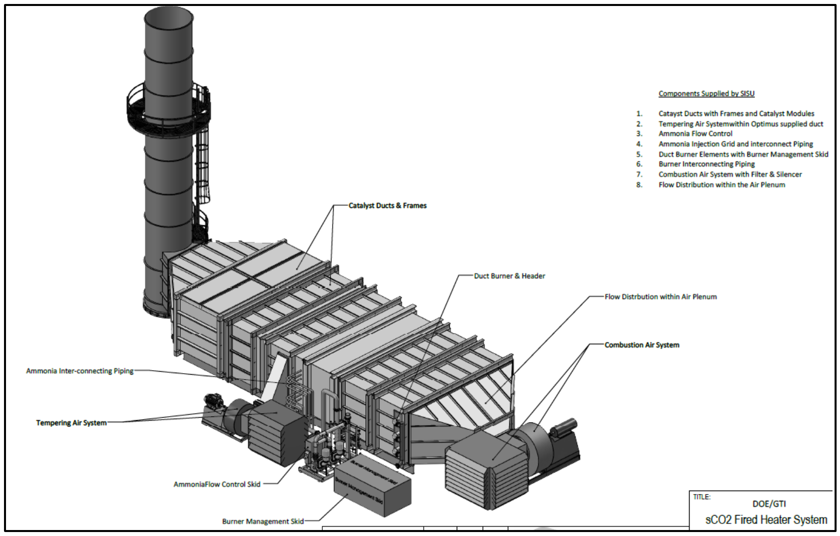


Figure 6. Schematic of STEP gas-fired heater

GTI is leading the procurement of major hardware including the heater, compressor, recuperators, and cooling tower. The heater is a natural gas fired with a tube bundle fabricated out of Inconel 740H to accommodate the >700°C, 250 bar sCO_2 conditions. It is based upon a duct-fired Heat Recovery Steam Generator (HRSG). The design is completed and materials ordered. A schematic is shown in Figure 6.

The compressor will be sourced from GE Oil & Gas Baker Hughes, and leverages an existing commercial product line as well as work undertaken in the DOE-funded Apollo program.

The heat exchangers include the high-temperature recuperator (HTR), low-temperature recuperator (LTR), and cooler. All units are planned to be compact heat exchangers with high surface area/volume ratios. GTI is currently engaging several vendors to discuss their product offerings and their suitability for the STEP operating conditions. Candidate exchangers include printed circuit heat exchangers [PCHE], micro-tube and shell exchangers, and other technologies. Example technologies are shown in Figure 7. At this time, the HTR has been ordered and will be a PCHE-type with a 50 MW_{th} capacity.

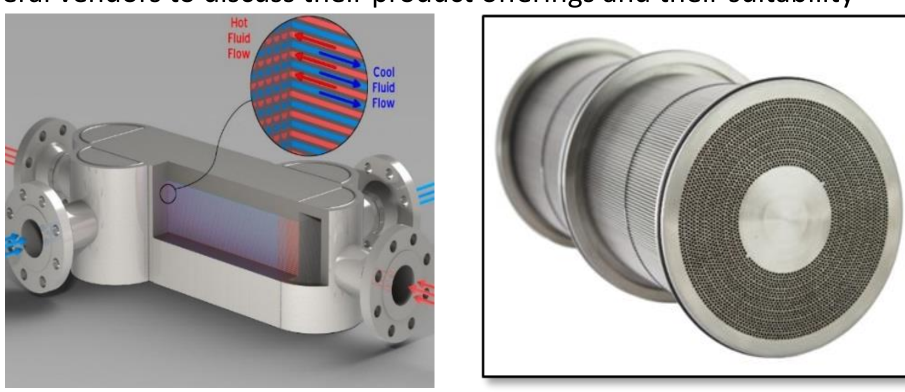


Figure 7. Examples of compact sCO2 recuperators

Summary

Supercritical CO_2 power cycles promise substantial cost, emissions, and operational benefits that apply to a wide range of power applications including coal, natural gas, waste heat, concentrated solar, biomass, geothermal, nuclear, and shipboard propulsion.

The STEP 10MWe program will advance the technology readiness level of this promising technology from TRL of 3 level to a TRL of 7. The project is well underway, with groundbreaking at the SwRI site in October 2018. A strong team is in place and executing smoothly. Additional partners are welcome. Further specifics on the Joint Industry Program are described below.

STEP DEMO

Joint Industry Program

A Joint Industry Program (JIP) team has been formed to support STEP Demo. This program has multiple industry partners who provide both funding and guidance for the project. It includes a Steering Committee with the U.S. DOE, project partners GTI, GE, and SwRI, and funding members. The Steering Committee ensures a collaboration process throughout the project life cycle. This is an open project and all parties—such as equipment manufacturers (OEMs), engineering companies (EPCs), owner/operators (utilities), energy companies, etc.—are welcome.

JIP STEERING COMMITTEE MEMBERSHIP

- US $250K (Cash) / year + in-kind contribution for 6 years
- Full voting membership on technical plans / direction
- Ability to guide program to best support member interests
- Direct participation in bi-monthly advisory meetings
- Attendance at bi-annual technical exchange meetings
- Real-time access to proprietary program data
- Opportunity for facility visits and training on equipment and operations at facility
- Receipt of quarterly status reports
- Receipt of technical reports
- Preferential opportunity to license system IP

JIP ASSOCIATE MEMBERSHIP

- US $100K/year for 6 years of the project or equivalent
- Attend in-depth, bi-annual technical interchange meetings in U.S.
- Receipt of quarterly status reports
- Receipt of technical reports
- Opportunity for facility visits

Project Partners

gti

SwRI Southwest Research Institute

GE

U.S. Department of Energy

National Energy Technology Laboratory

Steering Committee Members

KEPCO Korea Electric Power Corporation

Natural Resources Canada / Ressources naturelles Canada

Industry Partners

Southern Company

American Electric Power — Boundless Energy

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