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## SUPERCRITICAL CO2 POWER CYCLE PROJECTS AT GTI

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### ABSTRACT

GTI (Gas Technology Institute) is leading several sCO2 power cycle technology development projects. Three distinct projects are highlighted in this paper: (1) The 10 MWe Supercritical Transformational Electric Power (STEP) Pilot; (2) An indirectly heated coal/biomass-based Oxy-fired Pressurized Fluidized Bed Combustor (Oxy-PFBC); and (3) A novel high pressure oxy-combustor for direct-fired sCO2 power cycles. All three projects have significant systems engineering, optimization, operations analysis, controls, and partnership/ collaboration requirements.

In the STEP Pilot Project, a team led by GTI, Southwest Research Institute (SwRI), and General Electric Global Research, along with the University of Wisconsin and Natural Resources Canada, is executing a project to design, construct, commission, and operate an integrated and reconfigurable 10 MWe $sCO_2$ Pilot Plant Test Facility located at SwRI's San Antonio, Texas campus. This project is a significant step toward commercialization of sCO2 cycle based power generation and will inform the performance, operability, and scale-up to commercial power plants. The pilot plant design, procurement, fabrication, and construction are ongoing. By the end of this six-year project, the operability of the $sCO_2$ power cycle will be demonstrated and documented starting with facility commissioning as a simple recuperated cycle configuration initially operating at a 500ºC turbine inlet temperature and progressing to a recompression closed Brayton cycle technology (RCBC) configuration operating at 715ºC.

In the indirectly-heated Oxy-PFBC system, sCO2 is heated via a set of hermetically-sealed heat exchangers embedded in a footerbubbling bed of solid fuel (coal and/or biomass) particles that are combusted in a mixture of oxygen and recycled CO2 at about 8 bar. The resulting compact combustor lowers the capital cost, enables higher plant efficiencies and reduces CO2 capture costs.

In the sCO2 oxy-combustor project, GTI is designing a novel high-pressure oxy-combustor for direct-fired sCO2 cycles. The design concept, which is derived from rocket engine injectors, has potential to offer performance improvements over more traditional gas turbine-derived combustors.

### INTRODUCTION

The unique properties of supercritical $CO_2$ offer intrinsic benefits over steam as a working fluid in closed and semi-closed cycles to absorb thermal energy, to be compressed, and to impart momentum to a turbine.

The temperature and pressure threshold conditions required for supercritical $CO_2$ 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 [1]. Given these attributes, $sCO_2$ power cycles can offer several benefits [1,2,3,4]:

- Higher cycle efficiencies due to the unique fluid and thermodynamic properties of $sCO_2$

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- Reduced emissions resulting from lower fuel usage
- Compact turbomachinery, resulting in lower cost, reduced plant size and footprint, and more rapid response to load transients
- Reduced water usage, including water-free capability in dry-cooling applications
- Heat source flexibility

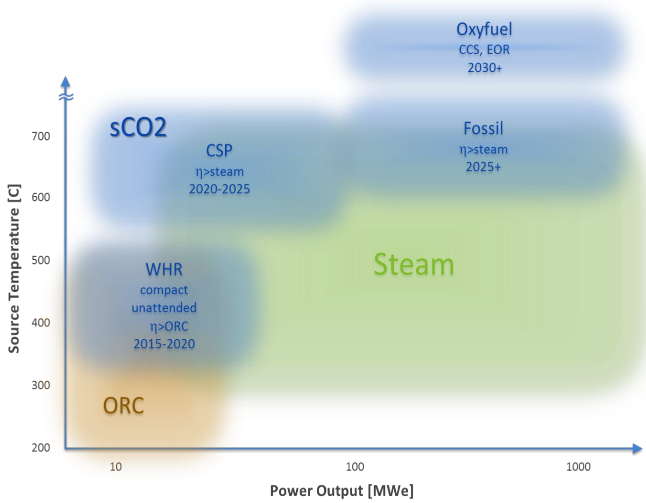


**Figure 1** – sCO2 Applications Map

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 [2].

GTI (Gas Technology Institute) is leading several technology development projects that seek to advance the status of the sCO2 power cycle technology across a range of potential applications. The STEP Project is a 10 MWe pilot demonstration indirect sCO2 cycles that are directly applicable to WHR, CSP, and Fossil applications shown in Figure 1. The oxy-PFBC is a solid fossil fuel (and/or biomass) technology, while the direct cycle oxy-combustor project relates to Oxyfuel applications.

In leading these efforts, GTI is providing the necessary systems integration, optimization, and operability/controls required by all three projects. In addition, GTI is leading the partnership coordination and development efforts required to successfully execute the projects.

More detailed descriptions of the three projects appear below.

## 1. STEP PROJECT

To facilitate the development and commercial deployment of the indirect $sCO_2$ cycle at elevated turbine inlet temperatures, pilot-scale testing is required to validate both component and system performance under realistic conditions at sufficient scale. The STEP (Supercritical Technology for Electric Power) project 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:

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

The STEP project 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).

The objectives include:

- Demonstration of the operability of the Supercritical Carbon Dioxide ($sCO_2$) power cycle
- Verification of the performance of components including turbomachinery and recuperators
- Demonstration of the potential for producing a lower cost of electricity in relevant applications
- Demonstration of the potential for a thermodynamic cycle efficiency of greater than 50%
- Demonstration of a 700ºC turbine inlet temperature or higher
- Validation of a recompression closed Brayton cycle (RCBC) configuration that can be used to evaluate system and components in steady state, transient, load following and limited endurance operation
- Reconfigurable facility to accommodate future testing:
    - System/cycle upgrades,
    - New cycle configurations such as cascade cycles and directly fired cycles,
    - New or upgraded components (i.e. turbomachinery, recuperators and heat exchangers)


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## Project Organization and Scope

GTI, SwRI, and GE-GR have formed a team to execute the STEP Demo project in line with program goals and objectives. This is a $119 million private/public partnership with significant funding from the US Department of Energy (DOE). GTI is responsible for overall management of the project and is performing technology management, systems engineering, major component procurements, and will participate in testing in a test management role. SwRI is providing the host site for the test facility, and is responsible for the facility design engineering, and construction of test facility, and the supporting utility infrastructure. As host site, SwRI will manage the hardware installation and system assembly, perform facility commissioning, and execute test operations. GE-GR is providing the technical definition for the turbomachinery, the turbo-expander by GE-GR in collaboration with SwRI and the compression system by Baker Hughes, a GE Company (BHGE), 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 near to completing over two dozen sCO2 technology related projects forming the building blocks for a successful STEP Demo [2,5,6,7,8,9,10].

A Joint Industry Program (JIP) team has also been formed to support the STEP Demo. This is an example of a consortium set up by GTI to 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. Current members include Korea Electric Power Corporation (KEPCO), Southern Company Services, American Electric Power (AEP), and Natural Resources Canada (NRCan). The Steering Committee ensures a collaboration process throughout the project life cycle.

The STEP Demo will be conducted in two major plant configuration 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.

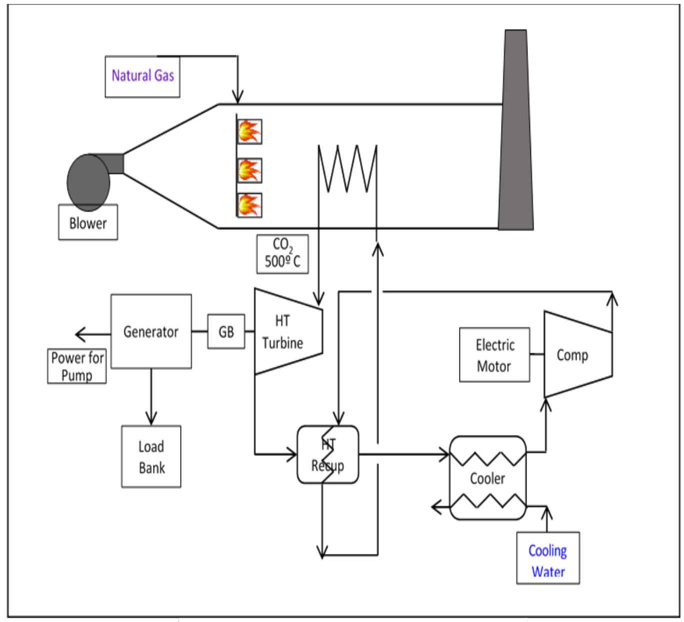


Figure 2a. Simple Cycle Configuration

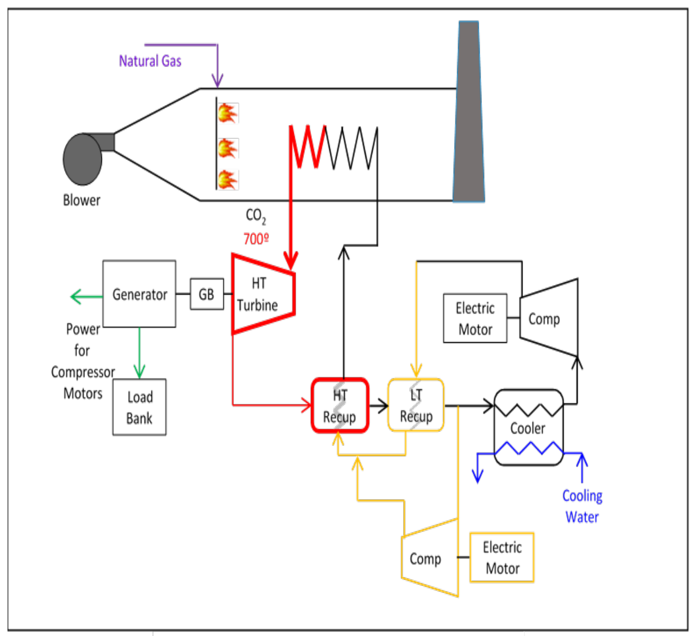


Figure 2b. Recompression Closed Brayton Cycle

A natural-gas fired heater that closely resembles a duct-fired Heat Recovery Steam Generator (HRSG) will supply heat. In Simple Cycle testing, $sCO_2$ fluid 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, as well as 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 goal of the program. In this phase, a second (lower-temperature)


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recuperator and a bypass compressor will be added. The turbine inlet temperature will be increased to the target level of 715°C.

**Cycle Conditions -** the different cases encompass the intended range of operating conditions for the facility. There are 2 Simple Cycle cases (max and min load) and 7 RCBC cases. The RCBC baseline case is the 10 MWe net cycle with a 715°C and 250 bar turbine inlet temperature and pressure condition. This RCBC baseline case sets the design requirements for the equipment, with the exception of the main cooler in which the simple cycle case was used. The remaining six RCBC cases are off-design conditions, varying sCO2 cooler exit temperature, turbine inlet temperature, and the method with which the cycle power level is reduced.

**Modeling** – GTI has completed steady-state modeling of all design and off-design cases, for both Simple Cycle and RCBC testing. Information from this study have been used to develop specifications for key components. In addition, transient models developed by both GTI and GE-GR are tools to simulate start-up, trip, shutdown and transient cases.

The transient models provide support to the development of the controls system and test planning. Two different software tools are used to model transient behavior: Flownex and Numerical Propulsion System Simulation (NPSS). The main components of these models include main and bypass compressors, turbine, high and low temperature recuperators, cooler, heater, pipes and valves. The thermal mass and CO2 fluid volume for each main component is based on vendor data or proven design practices. The validation of each main component with respect to steady state performance has been completed with vendor data. Due to the availability of published experimental data, only the HTR component model has been validated with respect to transient performance.

Testing done in the STEP project will generate data to verify the steady state and transient modeling tool predictions and enable confidence in commercial system design. A snapshot of the Flownex simple cycle configuration model is shown in Figure 3.

The phased testing approach will address specific technical risks while minimizing added complexity at each phase. In this manner, programmatic risk will be minimized by reducing unnecessary complexity and applying lessons learned from prior phases to address technical challenges.

**Schedule**

The STEP project was launched in October 2016, and is a six-year effort with three distinct budget periods.

BUDGET PERIOD 1 - (ENDED FEBRUARY 2019)

Detailed Facility and Equipment Design (28 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

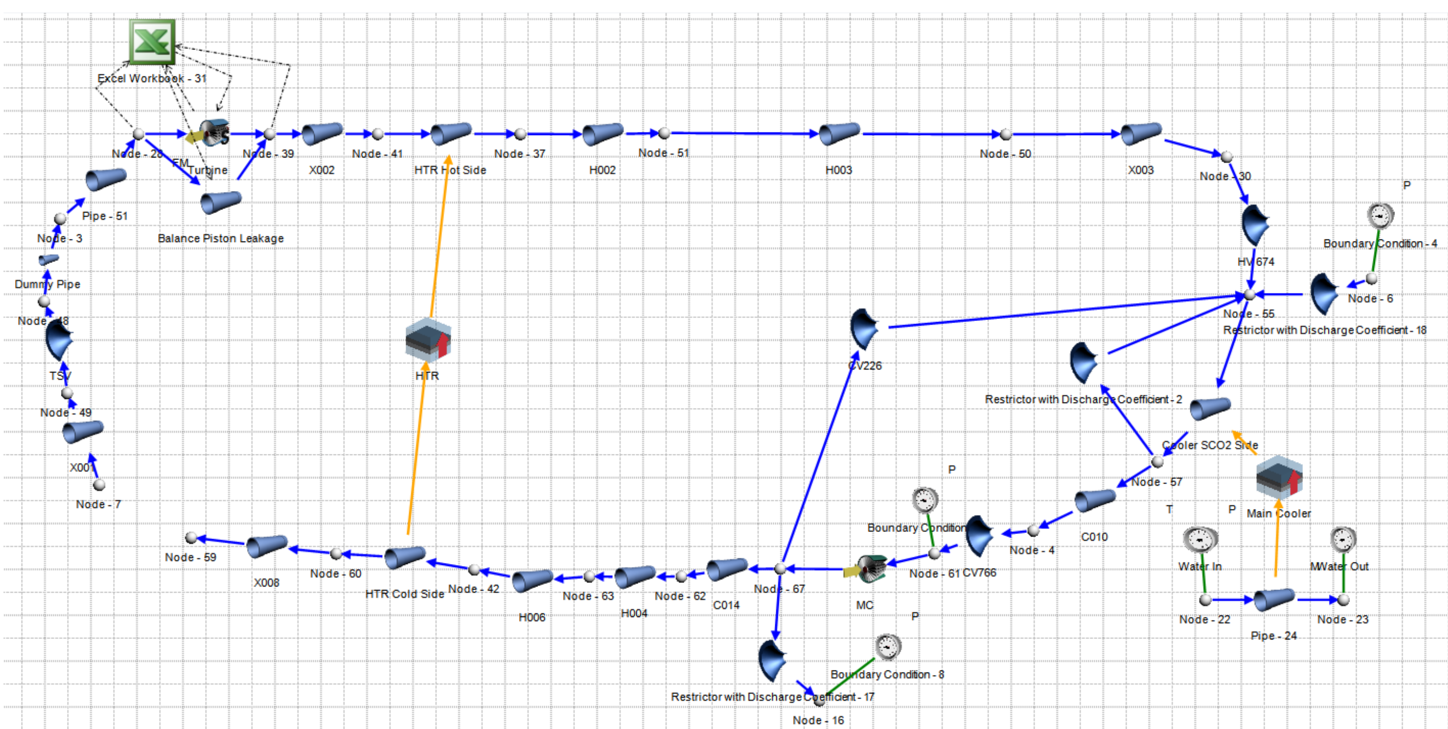


**Figure 3**– Flownex model concept



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BUDGET PERIOD 2 - (ENDS JANUARY 2021)

Fabrication and Construction (24 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**

The project involves the design, procurement, and construction of components and their integration. This is supported by several technology development tasks involving the turbine, turbine stop valve, materials testing, and modeling.

**Turbine Design** - conceptual schematics of the 16 $MW_e$ (gross) $sCO_2$ turbine, jointly designed by SwRI and GE, is shown in Figures 4 and 5. This effort advances an existing U.S. DOE-funded SunShot project in which SwRI and GE have fabricated and are currently testing a similar turbine [5, 9]. This SunShot project turbine was also designed for a turbine inlet temperature of 700°C but was successfully operated at reduced flow conditions, limiting power output to 1 MWe. The SunShot turbine is a 10 MWe frame size, the same as STEP but with a scaled gas path to 1 MWe to meet the existing flow loop capacity at SwRI. Despite, the power reduction, with the same inlet temperature and scale, the SunShot turbine is risk reducing key technology concerns. Figure 4 is the conceptual view of the initial STEP turbine case design and associated stand, which was based on the prior Sunshot turbine design. Figure 5 is the current STEP turbine configuration, which incorporates advanced aerodynamics to reduce stage count from 4 to 3 and thus allows and even more compact turbine.

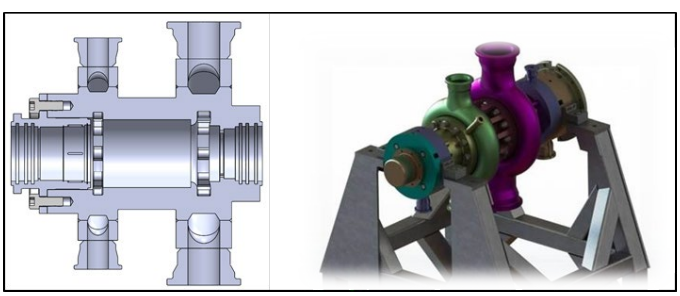

**Figure 4** - Conceptual design of 10 MWe STEP sCO2 Turbine

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, couplings on both shaft ends, and improved aerodynamic performance with an optimized volute flow area. The thermal management region will be enhanced based on lessons learned in the SunShot testing [11] and design enhancements developed under a related ARPA-E program [12]. Current STEP turbine design activities are focused on torsional train dynamics, rotor flow path preliminary design, and flow path mechanical and aeromechanical integrity.

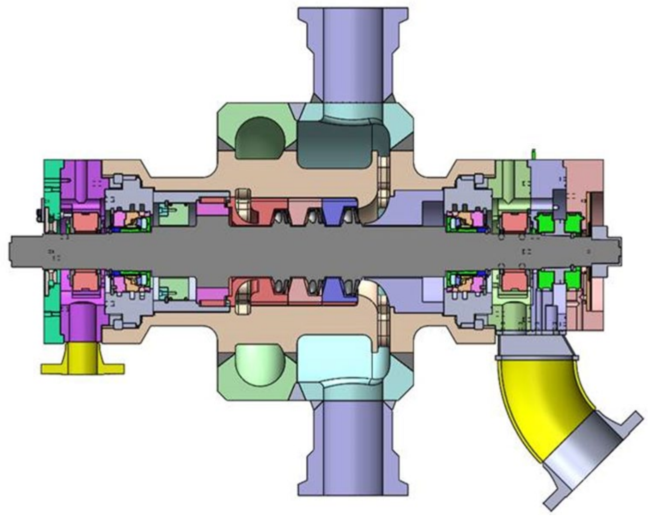

**Figure 5 -** 10 MWe STEP sCO2 Turbine

**Turbine Stop and Control Valve** - GE has completed the design of the turbine control/stop valve that 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 (Figure 6). Specifically, the valve material leverages efforts under advanced ultra supercritical (AUSC) steam power development programs for industry leading high temperature, high-pressure materials and components [13, 14, 16]

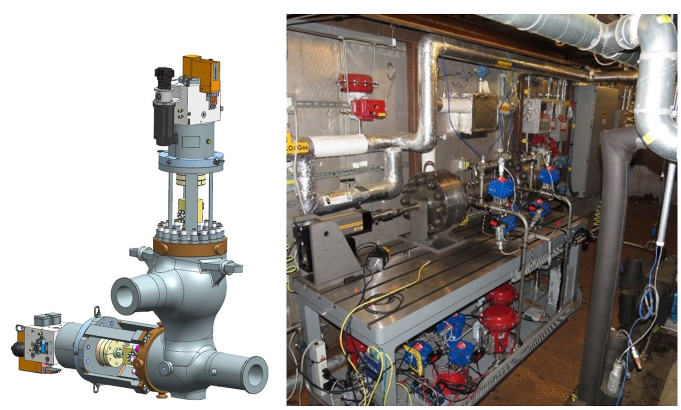

**Figure 6** – Turbine Stop Valve and Stem Testing at GE-GR



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**Compressor** - The compressor is being provided by GE Oil & Gas Baker Hughes (Nuovo Pignone), and leverages an existing commercial product line as well as work undertaken in the DOE-funded APOLLO program [15]. The APOLLO program is risk reducing the compressor performance of a real gas near its critical point. The APOLLO program has designed and is currently constructing a STEP-scale compression system to validate the enhanced real gas capable design tools over the wide operating range of the RCBC cycle. The validation testing occurred in the first half of 2019, providing guidance to the BHGE team for inclusion into the STEP compression system.

**Facility Design** - The facility is at a greenfield site on the SwRI campus in San Antonio, Texas. SwRI has completed the building layout and general arrangement plan (Figures 7 & 8), along with initial analyses of the interconnecting piping system [16]. The Environmental Assessment was completed by an external specialist and has been approved by the DOE. Site groundbreaking took place in October 2018.

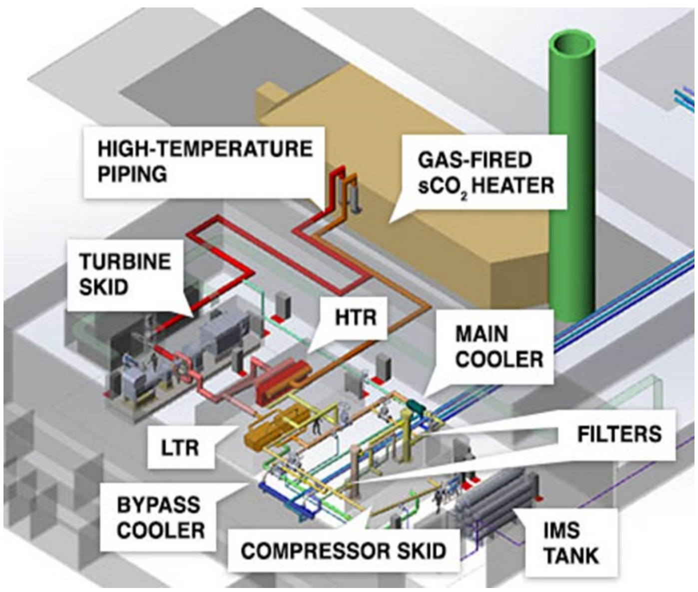


**Figure 7** – Equipment general arrangement

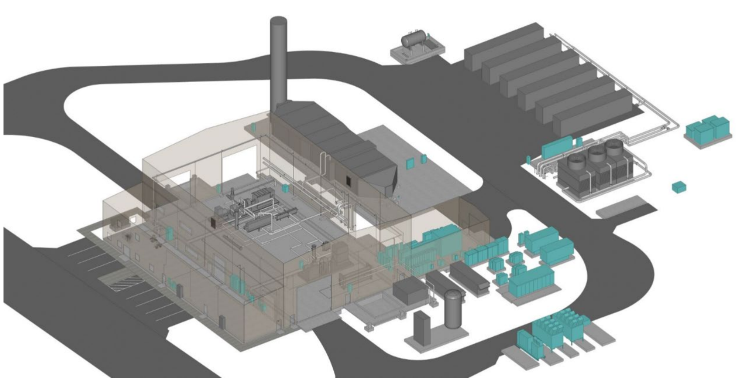

**Figure 8** –Building and Site arrangement

**Other Key Equipment** - GTI has procured major hardware including the heater, compressor, recuperators, and cooling tower [16]. Optimus Industries LLC is under contract for the heater. It is a natural gas fired unit with a tube bundle and high temperature headers and piping fabricated out of Inconel 740H to accommodate the >700°C, 250 bar $sCO_2$ conditions. Its arrangement is based upon a duct-fired Heat Recovery Steam Generator (HRSG) (Figure 9). The design is completed and is in production.

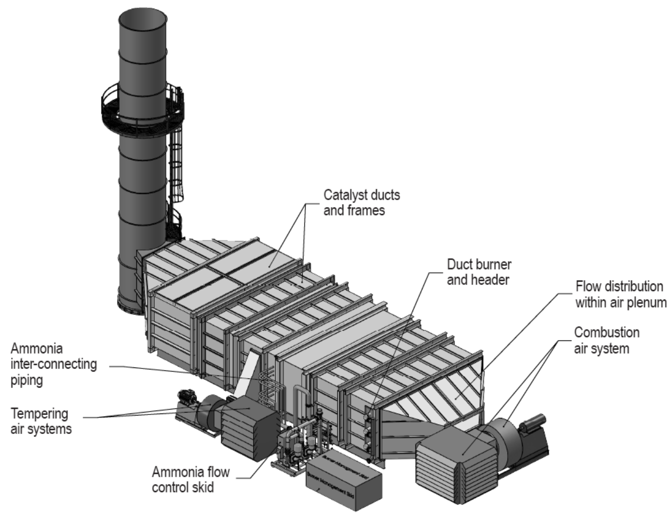


**Figure 9** - Gas Fired Heater with 740H material for 715°C sCO2

**Recuperators** - The heat exchangers include the High-Temperature Recuperator (HTR), Low-Temperature Recuperator (LTR), and coolers. All units are to be compact heat exchangers with high surface area/volume ratios. The HTR, LTR, and main cooler have been ordered from Heatric who will produce PCHE-type heat exchangers with thermal duties ranging between 13-49 MWth.

## 2. OXY-FIRED PRESSURIZED FLUIDIZED BED COMBUSTOR

GTI's Oxy-fired Pressurized Fluidized Bed Combustor (Oxy PFBC) is a highly integrated, innovative system designed to lower the capital and operating cost of clean power production. Pressurized combustion in oxygen eliminates the presence of nitrogen and other constituents of air, minimizing the generation of pollutants and enabling the economic capture of byproduct CO2. Oxy-PFBC is fuel-flexible, suitable for converting coal, petcoke, biomass or coal biomass blends into clean power.

GTI's Oxy-PFBC system was designed to minimize both the cost of the hardware and the levelized cost of electricity. It can be incorporated with a $sCO_2$ RCBC cycle for higher efficiency. One important feature of the Oxy-PFBC is the high power density combustor, which can eliminate hundreds of millions of dollars from the construction costs for a commercial scale


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power plant. The compactness of the combustor is largely enabled by two key features: high pressure combustion which shrinks the reactor size, and heat exchanger tubes submerged in the fluidized bed which significantly reduces the heat exchanger size. Another key to reducing system cost is the $CO_2$ purification unit (CPU) which also operates at pressure to reduce size and cost. The combination of air separation unit and CPU is substantially less expensive than comparable amine-based post combustion capture clean up equipment.

Key benefits of the Oxy-PFBC technology:

- Pressurized for smaller, less costly combustor (1/3 the size, ½ the cost)
- Can be coupled with sCO2 Brayton cycles for high plant efficiency
- Up to 98% $CO_2$ capture with coal, negative $CO_2$ emissions with biomass blends
- Produces purified $CO_2$ for chemical production or oil recovery
- Can produce steam for district heating or heavy oil recovery

GTI's Oxy-PFBC technology successfully completed component testing, and a 1 $MW_{th}$ pilot scale plant was installed at the Natural Resources Canada facilities in Ottawa where it was tested in 2017. It also included a $CO_2$ Purification Unit (CPU). The 1 MWth pilot testing achieved performance goals with the exception of carbon conversion. The combustor achieved oxy-combustion at the full target pressure of 8 bar. Two key combustor performance goals that were achieved include exceeding the target sulfur capture in the combustor as well as exceeding the acid dewpoint target at full operating pressure. This validated assumptions about the pressures that can be achieved without acid gas condensation and the associated corrosion risks. The ability to achieve target operating pressures supports combustor cost assumptions. In addition, the $CO_2$ processing unit (CPU), demonstrated a new technology, the deoxidation (DeOxo) reactor. The CPU achieved all of its performance targets, while the DeOxo reactor demonstrated the ability to achieve 100 ppm or less of oxygen in the flue gas stream to meet $CO_2$ pipeline specs. The combustor experienced issues with numerous temperature sensors that were buried and insulated by bed material. This led to anomalous operating conditions which caused lower than expected carbon conversion and hardware damage.

The vision for the Oxy-PFBC and sCO2 technologies is to combine them into a high efficiency, system for low cost carbon capture. The Oxy-PFBC and sCO2 technologies are currently being developed independently, with a future strategy of combining and demonstrating them as a synergistic system. This is illustrated in the integrated roadmap shown in Figure 10. GTI's Oxy-PFBC and sCO2 technologies both have multiple active programs continuing to advance the maturity of each in anticipation of a combined future demonstration.

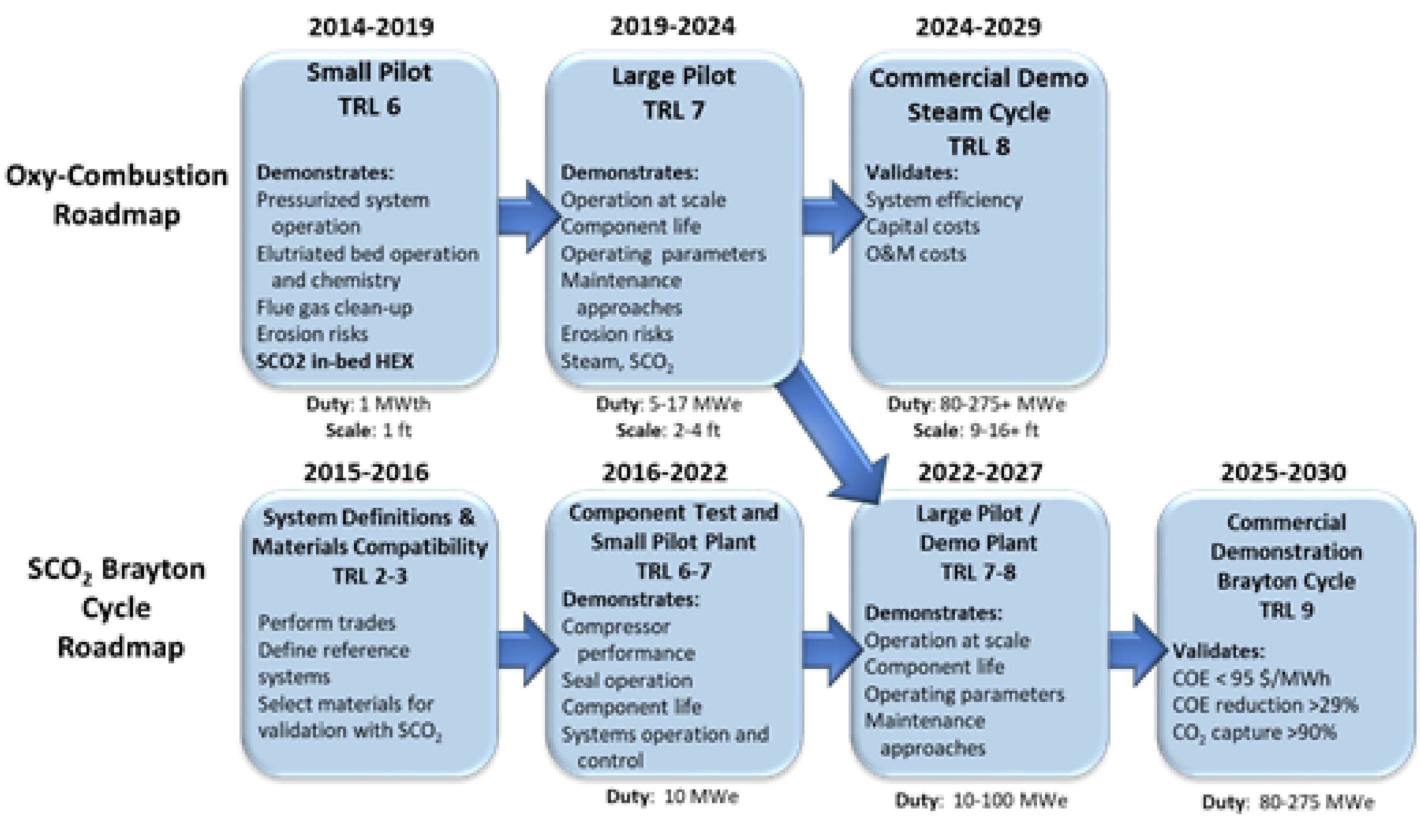


**Figure 10** – Integrated oxy-PFBC and sCO2 roadmap


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## 3. OXY-COMBUSTOR FOR DIRECT SCO2 CYCLES

GTI is also developing technology for direct-fired sCO2 cycle applications. The direct sCO2 cycle, shown in Figure 11, is characterized by high temperature and pressure turbomachinery that operates with sCO2 working fluid that is heated above 1150ºC at 300 bar in a pressurized oxy-combustor.

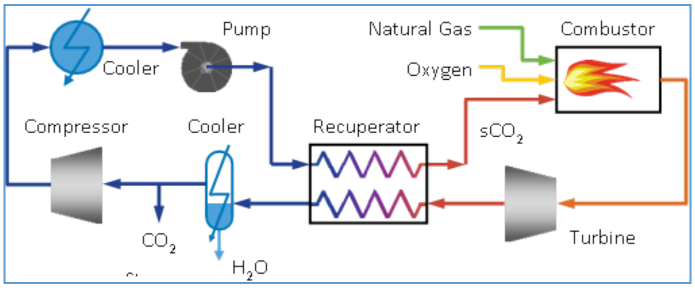


**Figure 11** – Direct-fired sCO2 cycle

The process conditions enable net cycle efficiencies from natural gas of over 50% (LHV basis) with near 100% CO2 capture [17]. However, sensitivity analyses have shown that the overall cycle performance is dependent on combustor performance. For example, any products of incomplete combustion (CO, unburnt hydrocarbons) and excess O2 degrade cycle efficiency [17].

This has highlighted a need for a high efficiency sCO2 oxy-combustor that would generate low products of incomplete combustion at low excess O2 levels. To address this need, GTI is leveraging its rocket engine combustor expertise and experience to design a novel sCO2 combustor. This expertise was obtained with GTI's acquisition of Aerojet-Rocketdyne's energy division in 2015.

GTI has developed a conceptual design and is currently exploring opportunities with partners to further develop and test a prototype combustor.

## 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. GTI is engaged in several projects that seek to advance the state of the art of the technology.

Firstly, the STEP 10MWe program will demonstrate indirect fired sCO2 cycles to known available materials limits (T>700C) in a fully integrated 10 WMe electric generating pilot. The project will enable the progression of technology readiness level from TRL of 3 level to a TRL of 7 and subsequent commercialization. The project is well underway. A strong team is in place and is executing smoothly. GTI has also developed the oxy-PFBC technology that burns coal and/or biomass under pressurized oxy-combustion conditions to enable low-cost CO2 capture. The technology is compatible with high temperature RCBC sCO2 indirect cycles. This combination of high sCO2 cycle efficiencies and relatively low oxy-PFBC capex has potential to lower levelized cost of electricity for power plants with near-zero CO2 emissions. GTI is also developing a novel combustor for direct-fired sCO2 cycles. This combustor, based on rocket engine concepts, has potential to improve combustor performance, improving overall cycle efficiencies for direct cycles.

A common theme between all three activities is the significant systems engineering, optimization, operations analysis, controls, and partnership/collaboration efforts required to successfully execute the projects.

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