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The STEP 10 MWe sCO_2 Pilot Demonstration Status Update

John Marion
Gas Technology Institute
Des Plaines, IL, USA

Scott Macadam, Ph.D.
Gas Technology Institute
Houston, TX, USA

Aaron McClung, Ph.D.
Southwest Research Institute
San Antonio, TX, USA

Jason Mortzheim
General Electric Global Research
Niskayuna, NY, USA

ABSTRACT

The Gas Technology Institute (GTI®), Southwest Research Institute® (SwRI®) and General Electric Global Research (GE-GR) are executing the Supercritical Transformational Electric Power, "STEP" project, to design, construct, commission, and operate an integrated and reconfigurable 10 MWe sCO_2 [supercritical CO_2] Pilot Plant Test Facility. The $156* million project is funded $115 million by the US DOE's National Energy Technology Laboratory (NETL Award Number DE-FE0028979) and $41* million by the team members, component suppliers, and Joint Industry Program (JIP) members. The facility is currently under final assembly and is located at SwRI's San Antonio, Texas, USA campus. This project is a significant step toward sCO_2 cycle based power generation commercialization and is informing the performance, operability, and scale-up to commercial plants.

Significant progress has been made on this STEP project. The design phase is complete (Phase 1) and included procurements of long-lead time delivery components. Now well into Phase 2, a ground-breaking was held in 2018, and civil work and the construction of a dedicated 22,000 ft^2 building was completed in 2020. Most major equipment is in final fabrication or delivered to site as of the end of 2021. These efforts have already provided valuable project learnings for technology commercialization. At time of paper writing most equipment has been received and installed, and commissioning will begin in the first half of 2022. An update on commissioning and experience with sCO_2 equipment is given here-in.

Figure 1 – STEP systems engineer, Dr. Scott Macadam (GTI) holding model STEP turbine rotor in front of new high bay

INTRODUCTION

Supercritical CO_2 (sCO_2) power cycles are Brayton cycles that utilize supercritical CO_2 working fluid to convert heat to power. They offer the potential for higher system efficiencies than other energy conversion technologies such as steam Rankine or Organic Rankine cycles; especially when operating at elevated temperatures[4]. sCO_2 power cycles are being considered for a wide range of applications including fossil-fired systems, waste heat recovery, concentrated solar power, and nuclear power generation.

*includes capital investment in facility building

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 supercritical state of CO_2 (nominally above 31°C (88ºF) and 7.4 MPa (1070 psia)) is easily achieved, and above these conditions is a supercritical fluid with compressibility but with higher density compared to steam or air. This results in much smaller turbomachinery (factor 10:1) for a given power level [4,5].

Given these attributes, sCO_2 power cycles can offer several potential benefits [4,5]:

- Higher cycle efficiencies due to the unique fluid and thermodynamic properties of sCO_2
- 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 in applicable site conditions.
- 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, nuclear power, and energy storage.

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 Demo (10 MWe net) 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

- 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% (defined as the ratio of net power generation to the thermal input transferred to the working fluid in the primary heater)
- Demonstration of a $\geq$ 700ºC turbine inlet temperature
- Validation of a Recompression Closed Brayton cycle (RCBC) configuration steady state and transient loads.
- Design and built a reconfigurable facility to accommodate future testing:
  - System/cycle upgrades,
  - New cycle configurations such as cascade cycles and directly fired cycles,
  - Integrated thermal energy storage
  - New or upgraded components (i.e. turbomachinery, recuperators and heat exchangers)

PROJECT SCOPE

Testing will occur in two configurations as shown in Figures 2a and 2b. The initial system configuration will be the sCO_2 Simple Cycle operated at turbine inlet temperature of 500ºC and pressure of 250 bar. The simple cycle configuration comprises a single compressor, turbine, recuperator, and cooler. 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 and lowest risk to obtain steady-state and transient data, while demonstrating controls and operability of the system, as well as performance validation of key components. This configuration is relevant to waste heat recovery applications for example from small simple cycle gas turbines. The 715ºC 250 bar RCBC configuration will demonstrate the highest efficiency potential achievable within the limits state-of-the-art known and approved materials.

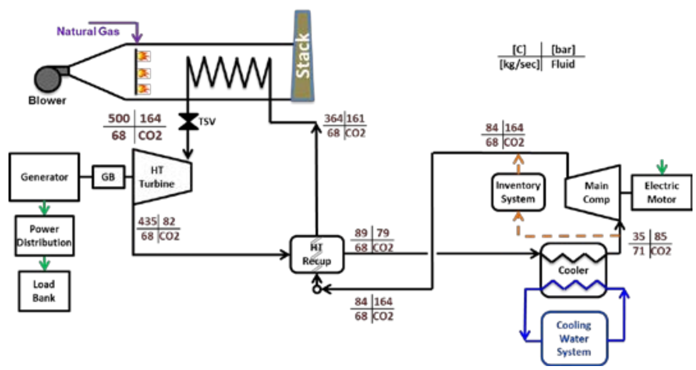

Figure 2a. Simple Cycle configuration

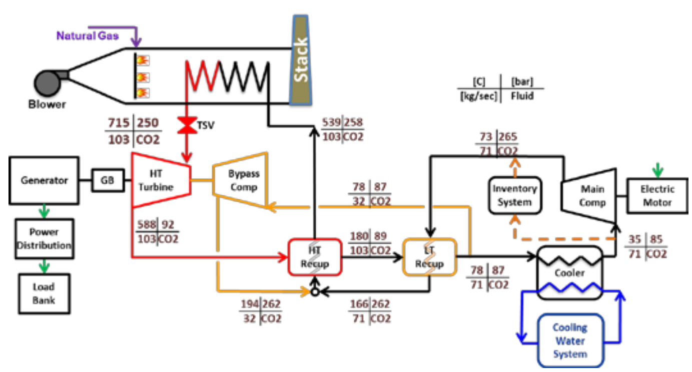

Figure 2b. RCBC configuration

PROJECT ORGANIZATION

GTI, SwRI, and GE are working as a team to execute the STEP Demo project in line with program goals and objectives. GTI is responsible for the overall management of the project and is performing technology management, systems engineering, major component procurements, and participating in testing. SwRI is providing the host site for the test facility, is responsible for the turbine design and fabrication, the facility design engineering, and construction of test facility and supporting infrastructure. GE Global Research (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 former GE Company (BHGE), as well as a first-of-a-kind sCO_2 turbine stop/control valve from GE Power. The combined team have completed or are near to completing over two dozen sCO_2 technology related projects forming the building blocks for a successful STEP Demo [1,2,3, 5, 8-14]. Of note is the successful 1 MWe class DOE SunShot program [8,12].

JOINT INDUSTRY PROGRAM

A Joint Industry Program (JIP) team has also been formed to support the STEP Demo and includes industry partners who provide both funding and guidance for the project. It includes American Electric Power, Southern Company Services, EGAT (Thailand), Engie (France), Korean Electric Power Company, Natural Resources Canada, Commonwealth Scientific and Industrial Research Organization (Australia), and the state of Texas TECQ office.

SCHEDULE

The STEP project was launched in October 2016 and is a multi-year effort with three distinct budget periods. As of the time of paper writing, the project is about 2 years delayed, mostly due to challenges with an immature supply chain supply for manufacturing of nickel alloy components at the scale required for the project (10 MWe).

BUDGET PERIOD 1 - (ended in 2019)

Detailed Facility and Equipment Design

• 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 - (forecast to end in 2023)

Fabrication and Construction

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

BUDGET PERIOD 3 - (ends in 2024)

Facility Operation and Testing

• Facility reconfiguration
• Test recompression cycle

PROJECT STATUS

The project involves the design, procurement, and construction of components, their integration, commissioning and testing to confirm performance and operability of a 10 MWe sCO_2 cycle based power plant. Now well into Phase 2, a ground-breaking was held in October of 2018, and civil work and the construction of a dedicated building facility is now complete. Most major equipment is in fabrication or delivered to site. Efforts have already provided valuable project learnings for technology commercialization. Previous progress reports in [1,2].

The Test Facility and Equipment Arrangement - The STEP Pilot Plant is housed in a newly constructed dedicated 22,000 ft2 General-Purpose Test Facility [GPTF] located on SwRI's campus in San Antonio, Texas (Figures 3 and 4). The facility includes an 80 MW_{th} Natural Gas Heater, a 25 MW_{th} cooling tower system, 3,250 tons of auxiliary chilling capacity, electrical interconnects for grid connected operation, and load banks for 16 MW_e gross turbine power when operating in island mode expected for first article acceptance or variable speed performance mapping. The STEP pilot has been designed for flexibility and reconfiguration into alternate cycle or hardware configurations for future test campaigns. Equipment layout given in Figures 5 & 6.

Figure 3 – Side view of STEP pilot facility

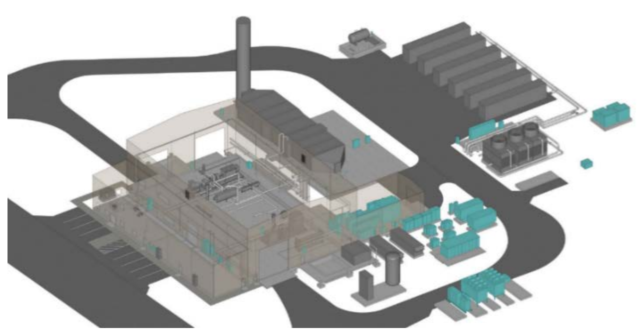

Figure 4. STEP facility and equipment layout

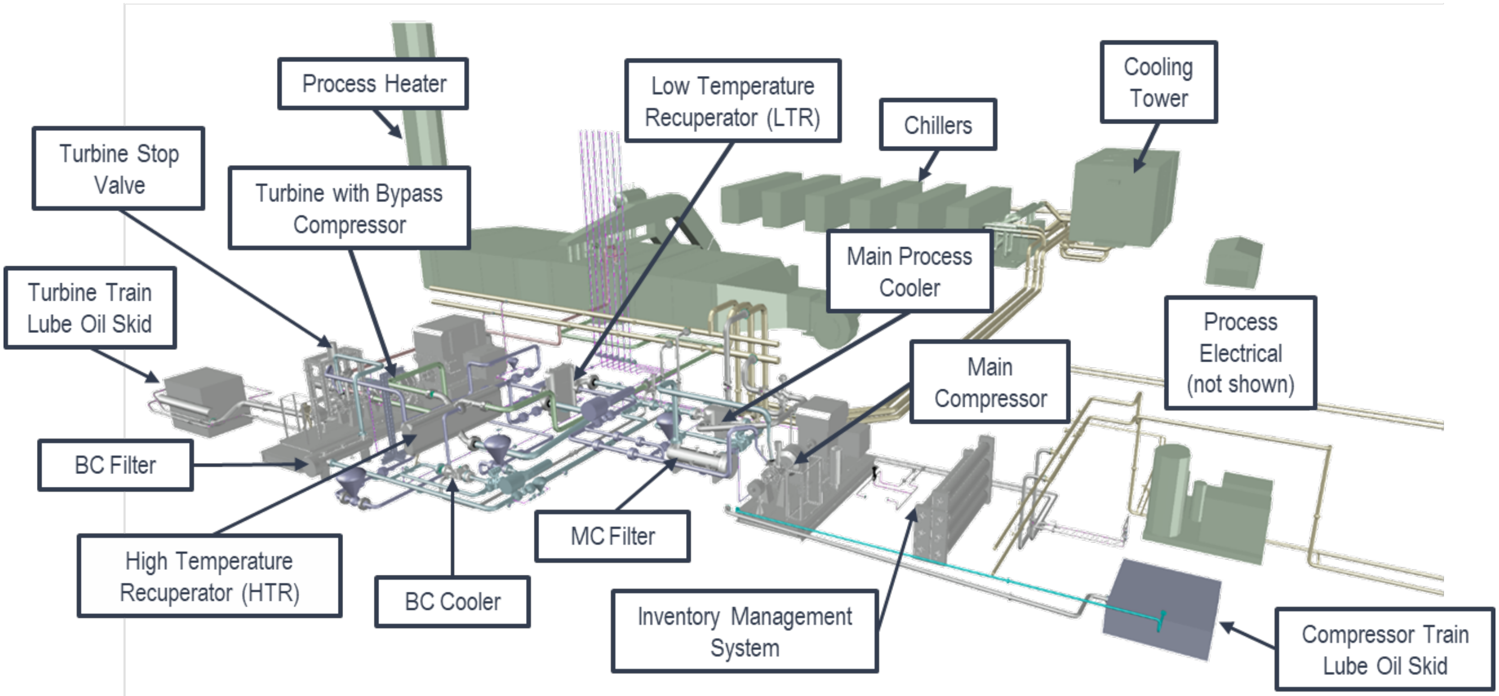

Figure 5 – 10 MWe STEP pilot power plant equipment arrangement

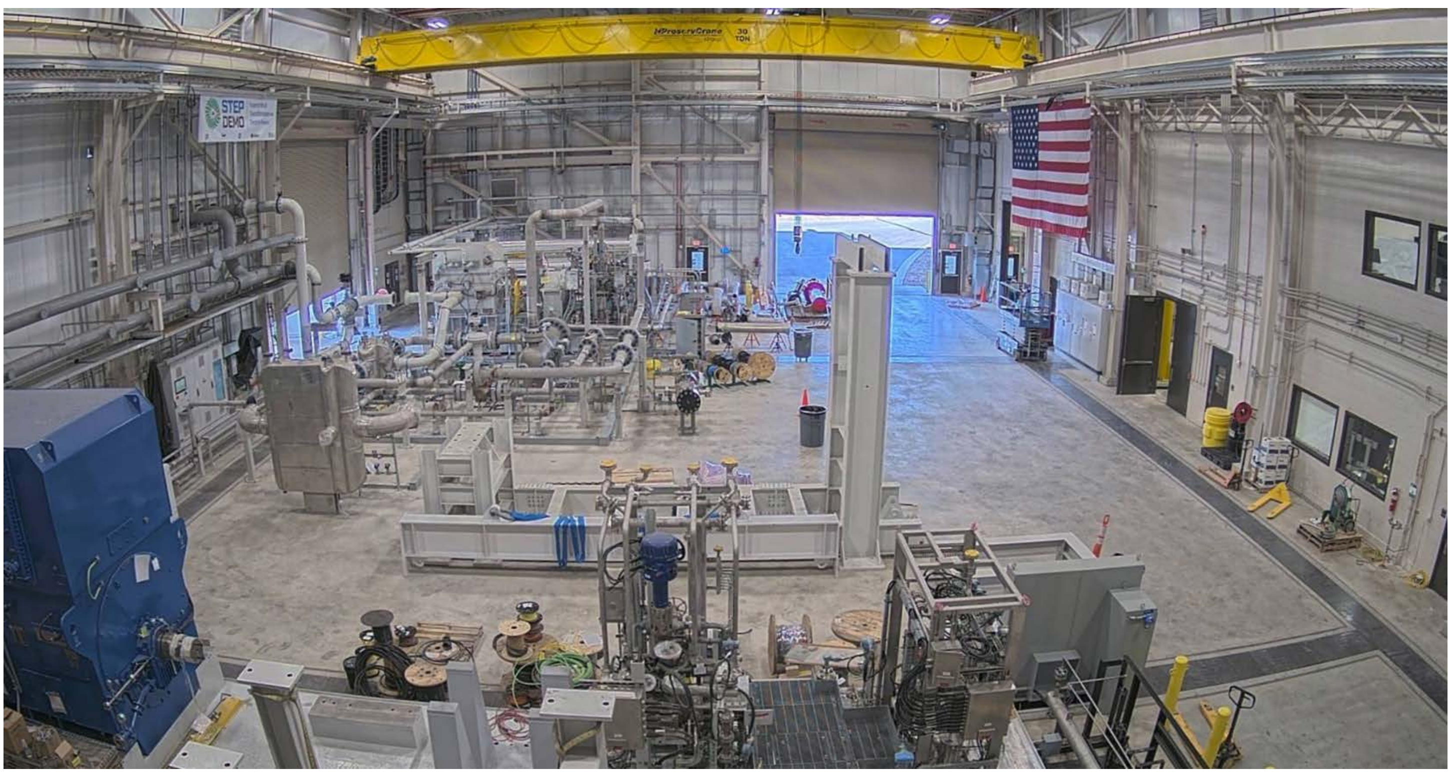

Figure 6 – Overall assembly of STEP pilot showing on-going welding of piping network as of February, 2022

Turbine –A schematic of the 16 MW_e (gross) sCO_2 turbine is shown in Figure 7. This STEP turbine advances the existing U.S. DOE-funded SunShot project turbine in which SwRI and GE have fabricated and successfully tested to 715ºC and 27,000 rpm [8,12]. The STEP turbine improvements include increased 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 is enhanced based on lessons learned in the SunShot testing [14] and design enhancements developed under a related ARPA-E program [14]. Turbine design details have published in [1,2,3,16]

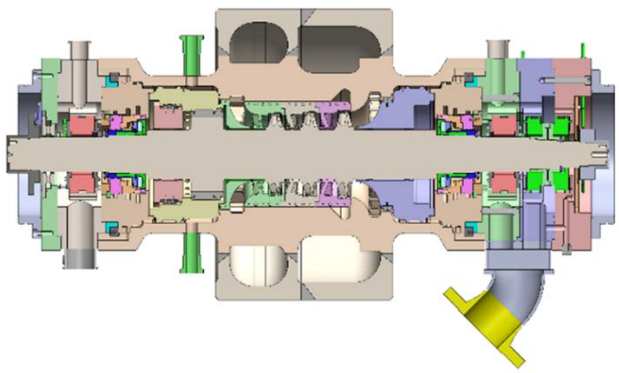

Figure 7 - 10 MWe STEP sCO_2 Turbine

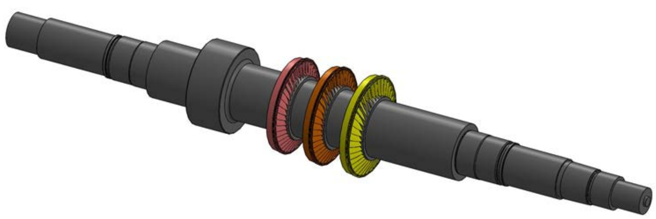

Figure 8 three stage monolithic STEP 10 MWe turbine rotor

Turbine Manufacturing – The 10 MWe STEP design creates manufacturing challenges over larger power equipment of similar power output. The turbine case with its small internal diameter relative to its length makes it challenging for machine tools to reach within the case to manufacture tight tolerances. Baker Hughes, having developed this capability to produce small compression system rotors, 5-axis EDM machined the monolithic STEP turbine rotor (Figure 9).

Figure 9 –Turbine Rotor EDM Second Stage

Figure 10 – Single piece Nimonic 105 multi-stage STEP turbine rotor

Figure 11 –Turbine Nozzles for each stage

Figure 11 shows the turbine stators 5-axis EDM machined and requiring several parts that create a bolted assembly.

The turbine casing (Figure 12) was fabricated from IN 625 for cost and schedule reasons, as well as an unfavorable experience with HA282 casting of the turbine casing in the predecessor SunShot project [12,13]. Application of IN 625 comes with a reduced embrittlement life limit, but well within the expected life of the STEP project.

Figure 12 –Turbine Casing – fabricated IN 625

Turbine Stop and Control Valve - Control of the flow to the turbine and shut off in an emergency situation requires a special control valve for the STEP plant which has been adapted from commercial steam turbine product line to accommodate sCO_2 fluid and the high operating temperatures. When needed for an emergency shutdown, it will close in under two tenths of a second.

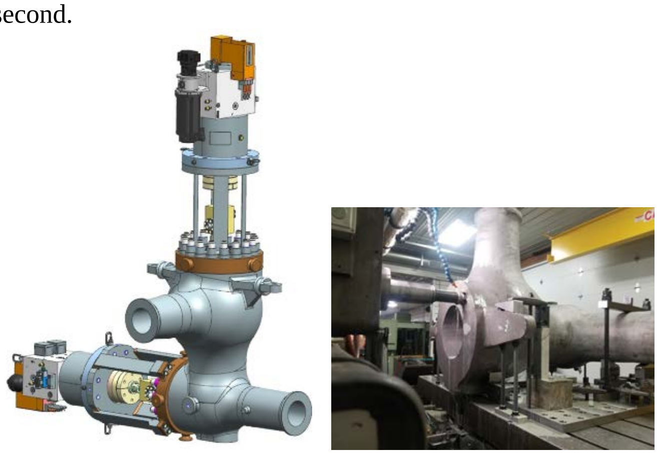

Figure 13 – a. Turbine Stop Valve and b. Body casting machining

Four unique features for the sCO_2 valve differ from that of standard industrial steam valves:

1. The use of Haynes 282 high temperature nickel alloy material leveraging efforts under AUSC steam power development programs for high temperature, high-pressure materials and components [17,18]
2. Density differences between steam and sCO_2 that required the use of high fidelity CFD to accurately predict internal flows and pressure balance.
3. Advanced stem sealing.
4. The use of compact self-contained actuators that more appropriately match the compact nature of the sCO_2 turbomachinery. This design is leveraged from commercial designs used by Baker Hughes.

For STEP, the valve body was cast with Haynes 282 nickel alloy for the high temperature and pressure duty (Figures 13a and 13b). The application of Haynes 282 for this valve and its casting technology was originally developed and trial cast in the DOE Advanced Ultra-supercritical Steam Power Plant Materials consortium project [17,18]. However, significant challenges have been experienced with the production casting for the 9,250 lbs (~5 tons) STEP demo TSV. Complexity and care in casting has been taken to achieve uniform material properties throughout the part and with minimal metal oxidation.

The HA282 TSV production continues to work through the casting process. The valve body, the largest and most geometrically complex part, has been cast and the casting is having surface inclusions ground out, and when required, weld build-ups made. This is a traditional process for a casting, although with the HA282 material, this process is slower than normal as the inclusion removal and weld repair needs to be controlled and slow to avoid excessive heating that could cause new cracks to form. For the simpler geometry heads, inclusions have been removed, weld repairs made where required, and the final machining is complete. Figure 14 shows one of the stop valve heads after final machining. The valve body is currently scheduled to be completed by 4Q 2022.

Figure 14 – SV Head cast being machined

Because of the manufacturing challenges encountered with this 715ºC TSV, an action was taken to additionally procure a lower temperature control and stop valve to meet project plans for simple cycle configuration testing. This valve is being fabricated with 316 stainless steel for <550ºC and 275 bar service. This valve has been procured from a European valve manufacturer with experience with similar design requirements. This valve is expected to be received at site in March, 2022

The STEP team views these manufacturing challenges as important learnings and part of the overall objective of this pilot demonstration. The cast body approach is consistent with normal commercial processes and with experience, manufacturing times, costs and reliability will likely improve. Emerging alternate approaches are also being explored outside of this project for example [19]. These alternatives are currently limited to small components, but with development promise further manufacturing improvement and thus cost reduction for these advanced alloy components.

Compressor - The compressors leverage an existing commercial Baker Hughes product line as well as work undertaken in the DOE-funded APOLLO program [20]. The compressor rotors are a monolithic design for the reduced size impellers inherent in this compact sCO_2 power cycle. Like the turbine, these have been 5-axis EDM machined by Baker Hughes in their shops in Florence, Italy.

Various operating scenarios have been discussed with Baker Hughes, including low-speed start of the compressor under liquid or two-phase conditions. During a pressurized hold, the sCO_2 loop will cool to ambient temperatures and liquid CO_2 formation is likely. Restart with liquid or dense phase CO_2 is required to avoid loop blowdown and control flexibility is a requirement with special care and monitoring to warm up under low load and avoid potential equipment damage.

Figure 15 – STEP main compressor skid

Figure 16 – STEP bypass compressor on turbine skid

Process Heater – The process heater is natural gas fired with high temperature pressure parts fabricated out of Inconel 740H for the >700°C, 250 bar sCO_2 conditions. Its arrangement is based upon a duct-fired Heat Recovery Steam Generator (HRSG). The high temperature IN740H fined tubing and 11.25” OD/ 7.5” ID diameter header are shown in Figures 17.

Figure 17 – IN740H tubing with 304 SS fins and welding tubing to 11.25” OD/ 7.5” ID diameter IN740 header

Fabrication of the heater coil progressed very well. However, stress relaxation cracking of IN 740H thin tube butt welds was experienced during post weld heat treatment (PWHT), but not in any of the header or tube to header welds. These cracks were diagnosed with help of NDE inspection both radiographic and PAUT [Phased Array Ultrasound Technique]. The later was developed and verified by EPRI specialists. Approximately two dozen cracked welds were identified in an 100% inspection of the approximately 1300 thin tube butt joints. These joints have been cut out and replaced with a small spool pieces, and subsequently retested including hydro tests with satisfactory outcome. The heater was inspected and passed ASME Pressure Vessel code certification. It was shipped to site in 2021 and is now fully assembled and ready for commissioning (Figure 18). The experience has been a valuable learning experience in weld procedures, heat treatments and NDE tools. It is separately being reported in [21].

Figure 18 - Gas Fired Heater with 740H material for 715ºC sCO_2

Recuperators – High performance and cost effective heat exchangers are critical to the performance and economics of sCO_2 power plants. As compared to a steam cycle, cycle mass flows are an order magnitude higher and a greater amount of heat must be recuperated in a sCO_2 power cycle to achieve efficiency targets. This results in very large heat exchangers if of conventional configuration. To address this, all of the main heat exchangers for STEP pilot are compact printed circuit-type [PCHE] designs which are more cost effective than conventional arrangements, such as shell-and-tube types.

Figure 19 Compact PCHE LTR sCO_2 Recuperator

Figure 20 – PCHE type main cooler

To date, the lower temperature heat exchangers (150ºC and 250ºC service) have been built and received at the site; Figure 19, Low Temperature Recuperator (LTR) (sCO_2 to sCO_2) and Figure 20 (Main Cooler)(sCO_2 to water).

The High Temperature Recuperator [HTR] operates with maximum hot inlet flow of up to 600ºC from the turbine exit. It has up to a 50 MW_{th} heat duty. The core of this heat exchanger is about 2' x 5' x 20' long, is made of 316 stainless steel and weighs ~50 tons. As compared to a solid block of steel, the void space of this heat exchanger is only about 10%.

This HTR operates over a wide range of conditions and two different power cycle configurations. A controlled cold-side flow bypass aids flexibility. However, the thermal-mechanical stresses over the operating range challenged acceptable local stress limit loads and cyclic fatigue design life. Finite element modeling included elastic-plastic analysis extensively performed by the vendor and the STEP team to arrive at an acceptable design for the heater, including the header nozzle locations and manifold design (Figure 21). At the time of paper writing, HTR fabrication is complete (Figure 22) and delivery to site is expected March 2022.

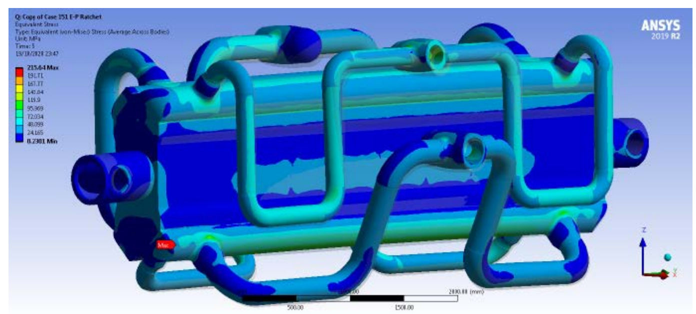

Figure 21– Finite element model of High Temperature Recuperator

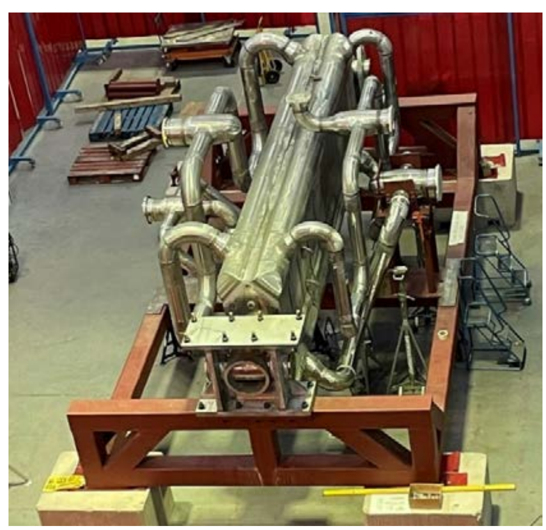

Figure 22 – High Temperature Recuperator at vendor facility after completion

System Modeling – For performance and operation, thermal-fluid simulations were conducted with Aspen™ for steady-state and FlowNex® for transient modeling, respectively. For this complex first-of-its-kind power plant, such models are critical for guiding operation and achieving performance goals while ensuring that the equipment stays within safe operation including such considerations as temperature limits, ramp rates, and temperature hold times.

The FlowNex® transient model was created to support the STEP project. It has been checked against the Aspen™ steady-state model, which was developed earlier over many years, and updated as the design and procurement of system hardware has progressed. Performance characteristics of the various components have been provided by the manufacturers and calibrated in the model to predict the expected results. The various heat exchangers in the system have been calibrated over a range of operating conditions to provide the expected outlet temperatures and pressure drops. To ensure accurate calculation of the compressor outlet pressure and temperature it is essential to have detailed fluid property definitions near the critical point. Thus, a new CO2 fluid file was created for this model using NIST REFPROP to improve the accuracy of the calculations. The mass, inertia, and frictional losses of all the components are input into the model so that transient effects are well captured. As commissioning and test data become available from the pilot plant, the model will continue to be validated and calibrated against the data to improve its accuracy and predictive capability.

An example from the FlowNex® transient model of an RCBC power level change from high to low power cases is shown in Figure 23 pressure (bar), Figure 24 flow (kg/hr), and Figure 25 power (MWe). During the transition, component setpoints need to adjust including turbine inlet temperature and compressor IGV position, and system mass needs to reduce and exit from the compressor discharge for storage in the vapor tanks. Sequencing and rates of change of these parameters were varied to study how system controls, pressures, and temperatures responded. For example, during the transition, the main cooler controls needed to show that the temperature into main compressor could be closely controlled and ensure that no liquid formation occurred at the entrance of the main compressor. The operating points of the main and bypass compressors on their compressor maps needed to be studied to make sure the compressors had sufficient surge margin. The HTR and the bypass compressor run at elevated temperatures close to their respective limits and so changes that affect the inlet temperatures needed to be monitored and controlled. The vapor tanks needed to be monitored as mass flows into them and the pressure and temperature increase such that structural limits are not exceeded and there is sufficient capacity to hold the mass at those conditions. Based on a number of these case observations and from the results of these simulations, proper operational procedures were tested and formulated.

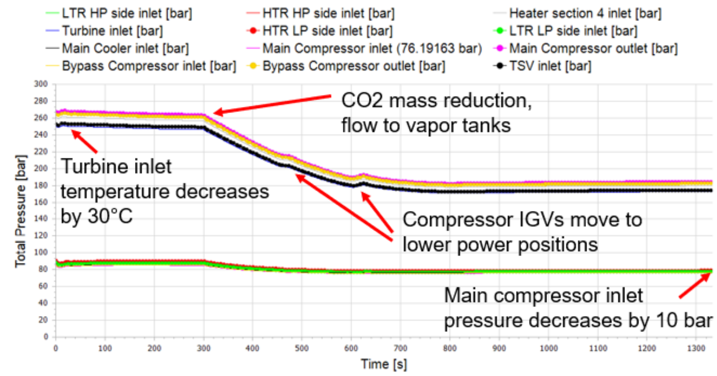

Figure 23 – RCBC power level change – **system pressures** (bar)

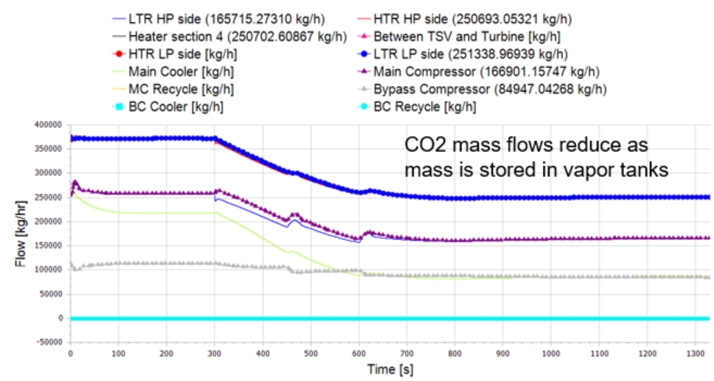

Figure 24 – RCBC power level change – **system flows** (Kg/hr)

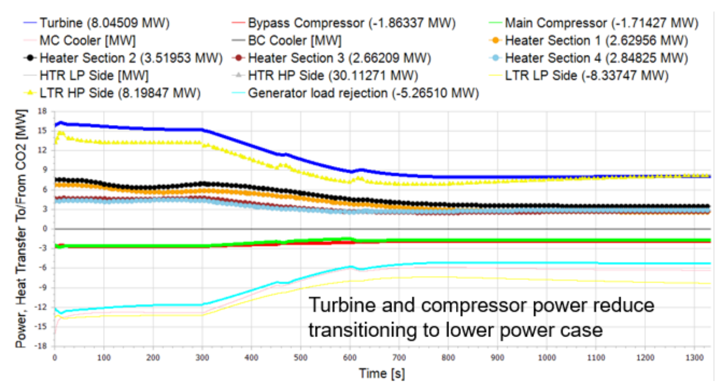

Figure 25 – RCBC power level change – **system power** (MWe)

Simulator - A simulator of the STEP 10 MWe pilot is also being developed. The FlowNex® transient model simulates the physics of the system hardware. The model ties into a GE virtual controller (STEP facility DCS is GE Mark VI), which has the same I/O points and logic as will be used in the actual facility. Real time process data and control system data is passed between the model and the controller. A simulator executive code controls the process model and the virtual controller to ensure that the two are run time synched. The virtual controller ties to a human machine interface (HMI), which mimics the actual data control

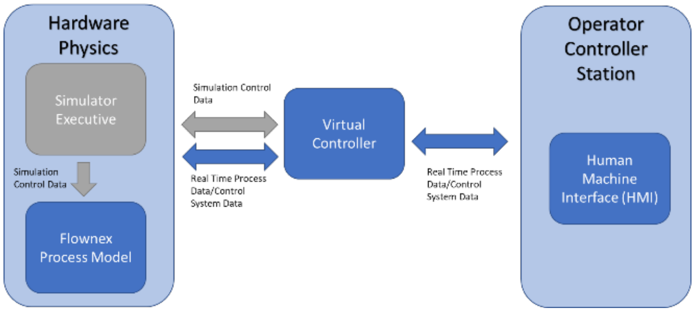

Figure 26 – Simulator approach

system of the facility. The HMI screens are the same as will be used in the actual facility as well. Real time process data and control system data is passed between the virtual controller and the HMI. A simplified schematic of the simulator is shown in Figure 26. Operators will complete training using this simulator to gain familiarity with loop system dynamics as well as to practice how to operate and control the system. By having the same DCS controller and HMI screens, an operator training on the simulator will have a similar experience practicing on the simulator as operating in the real plant. Overall, these modeling results are supporting controls narratives and controls programing. The modeling and simulator tools will also support operator training and future technology deployment. Steady state and transient modeling of design and off-design cases, for both Simple Cycle and RCBC completed prior is discussed in [1,2]

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 energy storage.

The STEP 10 MWe pilot demo project is demonstrating indirect fired sCO_2 cycles to known available materials limits (T>700ºC) in a fully integrated 10 MW_e electric generating pilot plant. 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 and commissioning in expected in 2022.

Acknowledgments

The authors would also like to acknowledge and thank the hard work of the team members of GTI, SwRI, GE and our other project participants, and gratefully acknowledge the U.S. Department of Energy, Office of Fossil Energy and Carbon Management and the National Energy Technology Laboratory, under Award Number DE-FE0028979, support for this work. The Joint Industry Program member's, (American Electric Power, Southern Company Services, EGAT, Engie, Korean Electric Power Company, Natural Resources Canada, Commonwealth Scientific and Industrial Research Organization (Australia), and State of Texas TCEQ) support and guidance is acknowledged and critical to the project.

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