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The STEP 10 MWe sCO_2 Pilot Installation and Commissioning Status Update

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ABSTRACT

The Supercritical Transformational Electric Power (STEP) project is currently commissioning a 10 MWe power plant to demonstrate high efficiency supercritical carbon dioxide (sCO2) power cycle technology. The project is led by GTI Energy® with team members Southwest Research Institute® (SwRI®) and General Electric Vernova Advanced Research (GEV-AR), with funding from the United States Department of Energy (DOE), National Energy Technology Laboratory. The total funding is $169M with $127M from the DOE and $42M from industry.

STEP project objectives include operating both Simple Cycle (SC) and Recompression Brayton Cycle (RCBC) configurations with turbine inlet temperatures of 500°C for SC and 715°C for RCBC. At 10 MWe, it is the largest indirect-fired sCO2 plant in the world, and will be used to demonstrate a pathway to 50% efficiency at larger commercial scales. The indirect-fired cycle is ideal for use with a variety of low/zero emission heat sources, including concentrated solar, nuclear, geothermal, biomass, waste heat, and carbon capture plants.

This paper provides an overview of recent STEP progress and key 2023 accomplishments including achieving mechanical completion for the plant and progress on commissioning. The paper provides an overview of recent installation activities and component commissioning for several pieces of major equipment including the turbine skid, compressor loop (main compressor, cooling tower, main process cooler and sCO2 inventory management system) and heater. An overview of recent progress on system commissioning is also provided.

This paper also discusses future work planned, including completion of system commissioning and testing of the Simple Cycle configuration. The next phase of the project, which will convert the Simple Cycle to an RCBC configuration, and conduct commissioning and testing at 715°C turbine inlet temperature to demonstrate maximum efficiency levels.

INTRODUCTION

The STEP project is the outgrowth of a comprehensive research and development program for supercritical CO_2 technologies that was established by the DOE more than ten years ago. This included a successful 1 MW loop demonstration named Sunshot of a sCO2 turbine operating at a turbine inlet temperature of 715°C at 250 bar and paved the way for the STEP project to step up to the commercially relevant 10 MWe scale[5].

The STEP project was broken into three phases. The first phase focused on design of the test facility from 2016-2019. The goal of the second and current phase of the project is to demonstrate Simple Cycle operation at 500°C turbine inlet temperature (Figure 1) in a simple recuperated configuration, which is a commercially relevant condition and scale for waste heat recovery applications, and finishes in June 2024. The third and final phase of the project is scheduled to start in July 2024, and will reconfigure the plant for RCBC operation at a turbine inlet temperature of up to 715°C, to achieve maximum performance (see Figure 2).

Objectives:

Demonstrate initial cycle performance with reduced risk configuration

- Single compressor configuration
- Turbine inlet near 500°C similar to WHR applications
- Provides steady & transient cycle performance data used to predict RCBC performance and operation

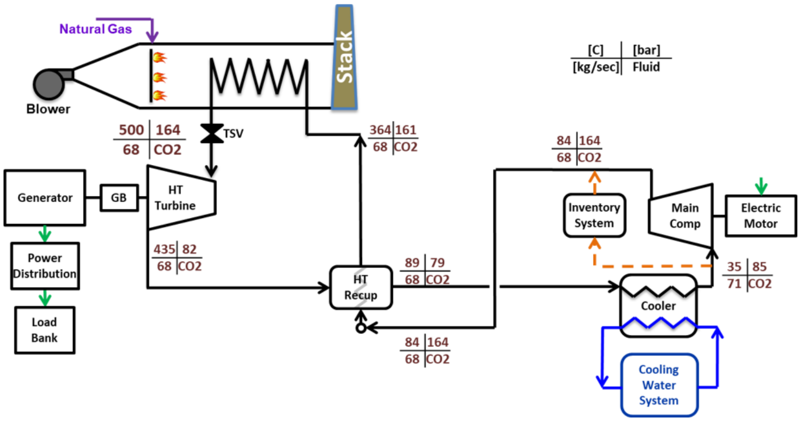

Figure 1. Simple Cycle Configuration

Objectives:

Demonstrate high performance cycle with parallel compressors and multiple heat exchangers

- Increase turbine inlet temperature to 715°C
- Measure steady & transient cycle performance data, evaluate operability
- Demonstrate pathway to 50% thermal efficiency

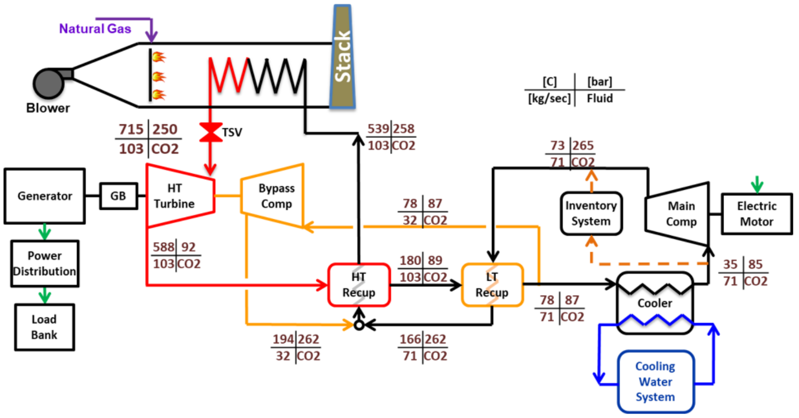

Figure 2. RCBC Configuration

Figure 3. The STEP facility was designed with room around the equipment to facilitate component swaps and cycle reconfiguration.

Benefits of SCO2

The supercritical carbon dioxide Brayton power cycle uses CO_2 under high pressure and high temperature supercritical conditions, as a closed-loop working fluid. Compared to a steam cycle, the cycle features more compact components such as turbomachinery that's 1/10th the size of conventional steam turbine systems[1,2]. It uses less fuel and consumes less water, and advanced configurations can enable zero emission power generation. This power cycle responds quickly and efficiently to changes in demand, enabling electricity grids to integrate base load generation with renewable solar and wind power. This versatile technology applies to diverse sources of heat, including turbine exhaust, concentrated solar, biomass, geothermal, nuclear, and industrial facilities.

RESULTS AND DISCUSSION

This section discusses the recent project achievements, as well as the challenges encountered and approaches to overcoming them. This is followed by an overview of the component status for the key turbine, compressor, and heater components, including their commissioning status.

Achievements

The STEP project recently reached three important milestones since the last published update in 2022[3]: achieving mechanical completion of the largest indirect-fired sCO2 power plant in the world, successful commissioning of the compressor loop, and the first demonstration of full system operation. Mechanical completion occurred in October 2023 and is the culmination of seven years of work towards an operational plant. It marked the completion of installation, and component acceptance testing and commissioning (where possible) of all equipment in the plant, so that the facility is ready to start system commissioning. A ribbon cutting ceremony was held to celebrate the event on October 27, 2023, as shown in Figure 4. The second milestone was commissioning of the compressor loop which demonstrated successful operation of the main compressor and associated compressor loop components, achieving target performance at the design point. The sub-system commissioning was completed in November 2023. Finally, the full system was operated under hot fire conditions for the first time in January 2023. This is the first time an indirect-fired sCO2 system has been operated at this scale.

Figure 4. Ribbon cutting for the STEP Demo facility, 26 October 2023. Pictured left to right: Jason Mortzheim, GE Vernova; Don Stevenson, GTI Energy; Texas State Senator José Menéndez; Robert Schrecengost, US Department of Energy; Adam Hamilton and Walter Downing, SwRI.

As the largest indirect-fired sCO2 power plant in the world, STEP also has what is believed to be the world's highest density terrestrial power turbine. Due to its compact size and the high density of sCO2 relative to steam, the STEP sCO2 turbine is more similar in power density to rocket engine turbines, rather than typical ground-based power turbines. The rotor weighs approximately 210 lbs (including couplings) for a power density of ~100 hp/lb (160 kW/kg) (see Figure 5). To put this in perspective, the STEP turbine, with its power output of approximately 21,000 horsepower (15.7 MW), is similar in size to a typical automotive V-8 engine, with an output that can vary from several hundred horsepower for a passenger car and 700 horsepower for a NASCAR racing engine.

STEP has also served as a catalyst to advance the application of high temperature materials, with several of the world's largest applications for these materials. The heater from Optimus contains the world's largest high temperature Inconel^{TM} 740H alloy heater tube bundle, with a design heat duty of 22.54 MW. The Heatric-manufactured high temperature recuperator is the world's largest high temperature printed circuit heat exchanger (PCHE), at ~38,330 kg (84,500 lbs), and is made of 316 stainless steel. The high temperature turbine stop valve, which will be utilized for RCBC testing, is the world's largest high temperature Haynes 282 casting at 9,250 lbs. Each of these items required advancements in one or more areas including design, manufacturing, and inspection methods. The advances in 740H fabrication during the course of the project were evident when the 740H process piping was installed in 2023. It was completed with nearly 100% weld success by taking advantage of lessons learned from the heater fabrication and using welders with prior 740H experience.

Figure 5. Rotor of STEP sCO2 turbine

Challenges

The STEP project has also faced a number of challenges as the technology is scaled up. These challenges include fabrication of high temperature components and materials at larger scales, developing components at small scale, and designing the facility for longevity.

The STEP project leveraged high temperature material development that was sponsored by the DOE for steam-based systems at ultra-supercritical conditions. Despite that previous work, there were still significant improvements in industry fabrication methods for high temperature materials that took place under the STEP project. This includes the heater, turbine stop valve, and high temperature recuperator.

The heater 740H tube bundle was fabricated with over 1600 welds, and required improved welding procedures and inspection techniques to enable successful production. While most of the welds were successful, 3% of the tube-to-tube butt welds failed inspection. An investigation of the failures found stress relaxation cracking during post-weld heat treat as the cause, and led to updated weld procedures and developed an improved inspection approach using 100% phased array ultrasonic testing.

The high temperature turbine stop valve, which is still in fabrication, also experienced challenges in casting the large amount of Haynes 282 nickel alloy required for the valve body. A new method was developed to cast Haynes 282, with a molten pour that used three simultaneous pours and methods to minimize oxygen entrainment which causes inclusions in the metal.

The high temperature recuperator was a significant design challenge, due to the temperature differential between the hot and cold side of the recuperator that causes it to bend into a banana-like shape due to the thermal growth differentials. This caused many design and architecture iterations to get to a design concept that could manage the thermal loads.

Another challenge was the small scale of the STEP turbomachinery. Since sCO2 is highly dense (similar to liquid water), the turbomachinery is an order of magnitude smaller than similar steam systems. This led to challenges with dynamic loads on the turbine shaft. An early plant design included the turbine shaft connected to a 3 MW generator and gearbox (to simulate the bypass compressor) on one end and the 13 MW generator and gearbox on the other. Due to the relatively large masses at each end and the relatively small diameter of the turbine shaft, it was found that the torsional dynamic loads in the case of a potential short circuit of the generators would be difficult to manage at this scale. This led to the decision to move the bypass compressor onto the turbine skid with only the main compressor on a separate skid driven by its own electric motor.

Component status and overview

Turbine

The objective of the STEP project is to advance the sCO2 turbine from TRL 6 (engineering prototype) to TRL 7 (full scale prototype). The turbine includes 3 stages with 16 MW shaft gross power output. Relative to the previous prototype tested for the DOE Sunshot project[4,5,6], advances include a full flow path (versus a partial flow path for Sunshot) to enable 16 MW power output, single inlet and single outlet connections (versus multiple for Sunshot), and a fabricated, single-piece barrel style casing (versus multi-piece bolted construction with multiple high-pressure seals for Sunshot) as shown in Figure 6.

The STEP turbine is mechanically complete and ready to start commissioning[7]. At this scale, the rotor and blades were fabricated as a single unit out of Nimonic 105 due to the high power requirements. However, this required long lead times for fabrication. At larger scales that will be typical for commercial power generation, individual blades should be possible, and is expected to simplify manufacturing and reduce lead times.

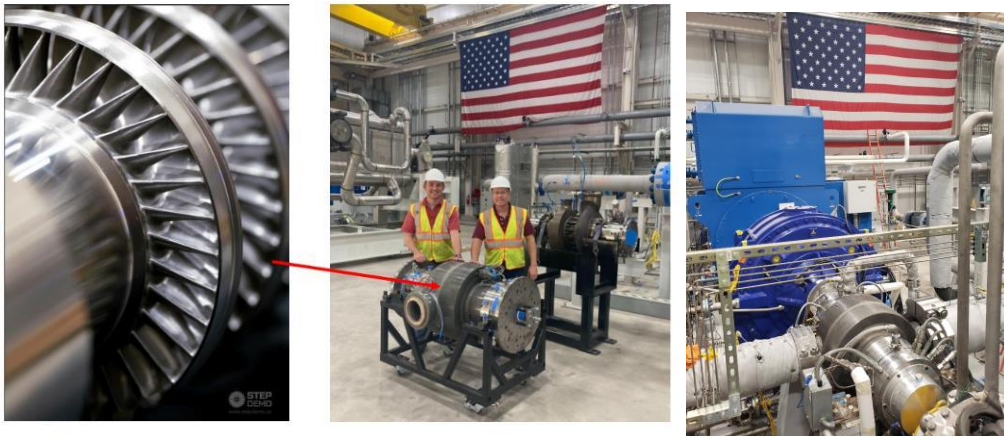

Figure 6. Turbine rotor, assembled turbine and fully assembled turbine train.

There were several lessons learned during the Sunshot turbine development regarding dry gas seals and the turbine case that were applied to the STEP turbine design. Thermal management is key to the health of dry gas seals, and it was found that delivery of warm seal gas is required at all times when the system is pressurized near the critical pressure (i.e. above 50 bar). By design there are turbine case vibrational modes that exist in the operating speed range. The case was designed to keep those modes at low speeds to minimize excitation and was validated by modal testing. The turbine ancillaries including the lube oil and dry gas seal systems were connected, flushed, and commissioned. The flushing involved installing jumpers with screens bypassing each piece of equipment. Flushing continued until no contamination was observed in the screens and particle counts in oil samples met ISO 4406 requirements for particle counts.

The turbine achieved its first rotation in December 2023. Due to the heavy generator rotor, break-away torque is high requiring a significant flow through the turbine to achieve rotation. The over-speed system, which is normally set to 5% above normal operating speed, was set to 1000 rpm turbine speed to ensure speed remains low. Moore et al. provides speed, vibration, pressure, and flow data for the turbine and compressor during this short transient[8]. The turbine stop valve tripped as designed and a maximum speed of 1600 rpm was achieved. The fast-acting turbine stop valve (TSV) closed within 200 ms as designed, and the train coasted down over a 90 second period. No unusual vibrations were observed during this short test. Testing in January demonstrated turbine operation up to 18,000 rpm with a turbine inlet temperature up to ~200°C. Future testing will expand the operational envelope to 27,000 rpm and 500°C turbine inlet temperature, while performing turbine abradable seal break-in, trim balancing (if required), and verification of all mechanical and vibration parameters at full speed, including the firing of the main heater.

Compressor

There are two compressors currently installed in the STEP facility: a main compressor for both Simple Cycle and RCBC operation, and a bypass compressor that will be used for RCBC only. The main compressor, which is a 2.7 MW single stage centrifugal compressor, operates at up to 27,000 rpm and is driven through a gearbox by an electric motor with a variable frequency drive. It is designed to operate at supercritical conditions and is also capable of operating in multi-phase conditions that include liquid. The ability to operate with liquid is important to support cool restart conditions in a test facility where CO_2 is left in the loop but may condense overnight due to cooling. Liquid operation enables the loop to be restarted without purging the CO2 system, saving time, money and CO2 emissions during test campaigns.

The main compressor loop was successfully commissioned in August 2023, and performance maps of the compressor were developed[9]. The compressor loop included the main compressor, compressor gearbox, compressor electric motor, cooling tower, main process cooler, and sCO2 inventory management system. Performance maps were generated at both 20,700 and 27,000 rpm conditions, at inlet pressures of 90 bar, and with inlet temperatures ranging from 34.6C to 45C. The actual performance maps were found to be significantly different than the maps provided by the vendor, with significantly less turndown than expected (Figure 7). Despite the difference with the performance maps, the compressor was still able to hit the performance guarantee point at the RCBC design condition. Further work is needed to understand what is causing this issue and how to resolve it.

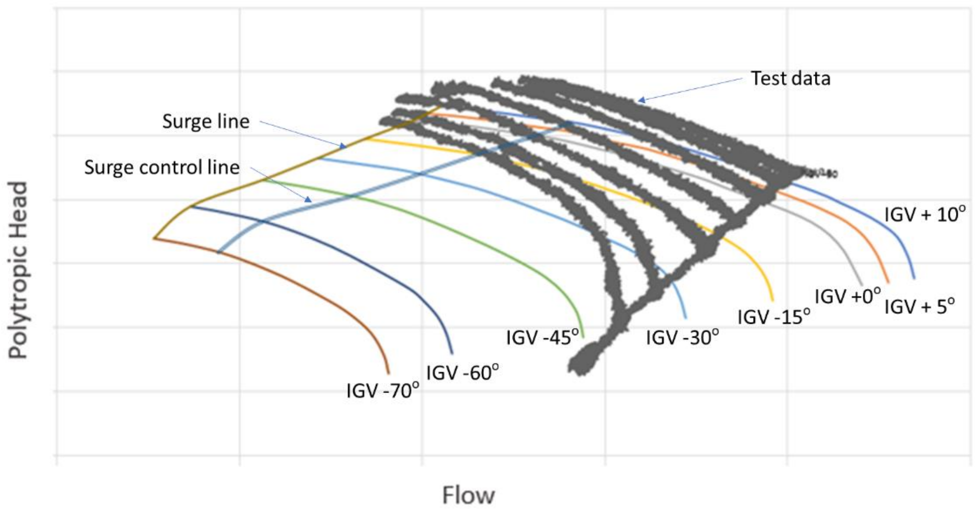

Figure 7. Compressor head versus flow indicates significant differences between vendor predictions (colored lines) and actual performance, with turndown (max flow / min flow) reduced by approximately a factor of two relative to pretest projections. The compressor was still able to achieve target performance at the RCBC design point.

Heater

The process heater (Figure 8) is a 93 MW$_{th}$ natural gas fired heater with high temperature pressure parts fabricated out of Inconel 740H to provide 100 kg/s of sCO2 at up to 715°C and 255 bar[10]. Its arrangement is based on a duct-fired Heat Recovery Steam Generator (HRSG). The heater was shipped to the site in 2021 and installed, and it went through acceptance testing in September 2023. The heater coil, rated at 22.54 MW, was the largest known application of Inconel 740H alloy to ASME Boiler & Pressure Vessel code construction.

Figure 8. The 93MWth heater completed acceptance testing and is now providing heat for system commissioning.

The heater is mechanically complete and acceptance testing at the site was completed. The selective catalyst reduction (SCR) emission control system was also installed. The heater was fired to support system commissioning tests for the first time in January 2024, and provided sCO2 to the turbine at up to nearly 200°C. The temperature history of the sCO2 entering and exiting the heater is shown in Figure 9, and the time window when the turbine was operating is indicated in the graph. The heater was successfully operated during the day without issue. As commissioning tests continue, the heater will provide sCO2 at gradually increasing temperatures up to 500°C to support full power operation of the Simple Cycle configuration.

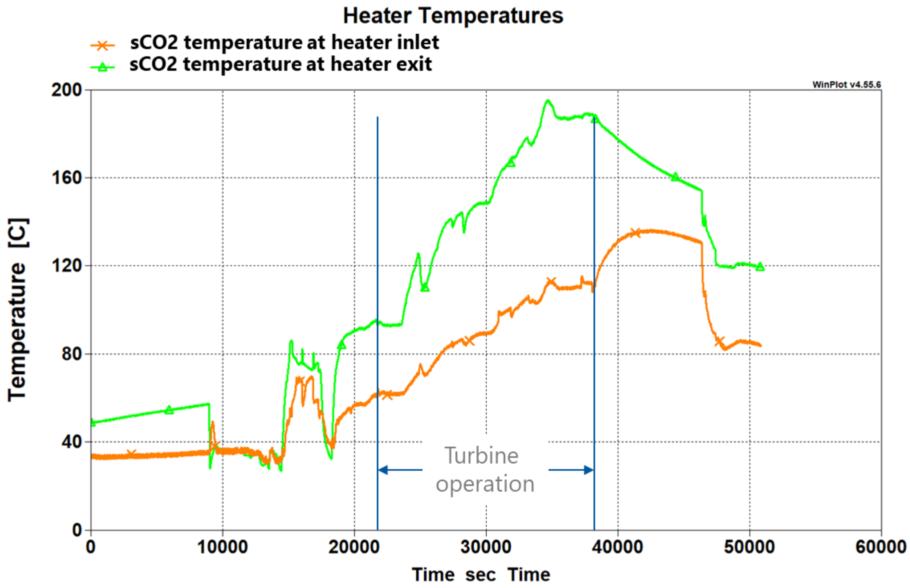

Figure 9. Heater operation during a system commissioning test in January 2024 delivered sCO2 approaching 200C during turbine operation. Future commissioning tests will ramp the temperature up to 500C.

Fabrication of the 740H heater coil included execution of over 1600 welds, with a low initial weld failure rate of ~1%. After post-weld heat treatment (PWHT), the only welds that failed were ~3% of the tube-to-tube butt welds. Phased array ultrasonic inspection was used to inspect 100% of the welds. A failure investigation was conducted[11] to determine the root cause factors. The failure mechanism was determined to be stress relaxation cracking during PWHT. The weld procedures were modified accordingly, and repairs were successfully completed. Follow-on research is focused on advanced characterization and development of industry guidelines for future application of 740H in high-temperature conditions. Lessons learned by Optimus were shared for the 740H facility piping installation effort.

Component commissioning of the heater activities reported here includes component commissioning of the heater through heater burnout. To run the heater for component commissioning purposes typically requires that it is connected to the rest of the STEP plant so that sCO2 can flow through the heater coil and cool it. However, to accelerate the schedule, there was a desire to commission the heater in parallel with other installation and commissioning activities. To enable this, a large air compressor was brough to the site and used to supply air to the heater tube bundle. The pipes to the heater were disconnected from the rest of the plant and connected to the air compressor which enables heater burnout activities to be conducted. This is required to burn out any residual material in the heater flowpath, such as oil, grease, or other debris which could contaminate the catalysts. Burnout was conducted with 4 hours of continuous operation at 700°F. The air flow was sufficient to keep the heater coil temperatures within acceptable limits during this operation. Once burnout was completed, the piping was reconnected to the plant, and catalyst installation was completed. Although the motivation to run the heater using relatively low pressure air cooling was for schedule purposes, a side benefit was that it also made the commissioning process easier due to reduced hazards associated with high pressure CO2 in the heater.

Conclusion

Mechanical Completion is the culmination of seven years of work towards an operational plant. It demonstrates that the equipment installation is complete, and the plant is ready to start system commissioning. There are numerous lessons learned so far from design, installation and limited testing completed prior to system commissioning that are relevant to commercial applications. One beneficial impact of the STEP project was the advancement of fabrication maturity for high temperature material at larger scales, with the largest applications to date for high temperature printed circuit heat exchangers for the high temperature recuperator, Haynes 282 casting for the turbine stop valve and Inconel 740H applications for the heater coil. For the compressor, gaps in knowledge regarding performance of commercial sCO2 compressors were identified, which represents a research opportunity to further refine and improve performance of these machines. It was also found that the ability for sCO2 compressors to operate with liquid CO2 is an important requirement to support more efficient facility operations and was achieved for this project. For the heater, it was found that commissioning the heater with air instead of CO2 is a useful approach to accelerate the schedule and simplify commissioning processes and safety procedures. Turbine lessons learned include the importance of providing warm gas to the dry gas seals at all times when the system is pressurized, and it was also found that some turbine case vibrational modes that exist in the operating speed range, so the case was designed to keep those modes at low speeds to minimize excitation.

Next steps

The project’s next steps, shown in Figure 10, are to complete system commissioning and simple cycle testing up to 500°C turbine inlet temperature in early 2024. The team aims to secure industry cost share and DOE approval to proceed into the final budget period 3, which will reconfigure the pilot plant to the Recompression Closed Brayton Cycle configuration and complete testing up to the full 715°C operating potential of the plant. This is expected to extend into late 2025.

After the project is completed, the facility can be made available for use by industry to develop and test components and cycle configurations.

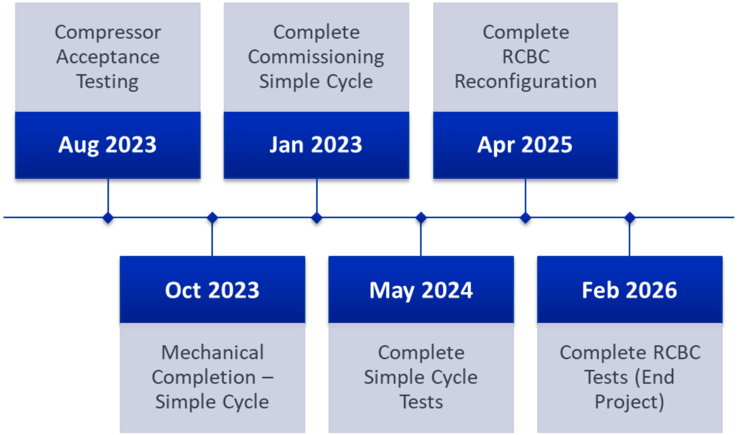

Figure 10. Next steps include completion of Simple Cycle commissioning and testing in early 2024, with RCBC testing completed in late 2025.

DISCLAIMER

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