Testing of the STEP 10 MWe sCO2 Power Plant in Simple Recuperated Cycle Configuration and Model Comparisons

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Abstract. The 10 MWe Supercritical Transformational Electric Power (STEP) Demo pilot plant has completed its first phase of testing and has achieved full operational speed of 27,000 rpm at a target turbine inlet temperature of 500°C in the Simple recuperated Cycle (SC) configuration. This milestone was achieved while synchronized with the electrical grid generating a gross turbine aerodynamic power of 8.3 MW (11,500 hp) and approximately 4 MWe of net power to the grid. This is the highest capacity to date in the world for indirect-fired sCO2 power technology. This $170 million project is a partnership between GTI Energy, SwRI, GE Vernova, and the US DOE. Mechanical completion was achieved in October 2023. In May 2024, the plant ran and generated electricity for the first time. Subsequent testing continued leading to the maximum power in the SC configuration achieved in September 2024. The results of testing of the plant's major systems including the compressor and turbine machinery trains, the cooling tower system, the heater, inventory management system, and heat exchangers generally show performance in line with expectations and simulation modelling. The next phase of the project will transform the pilot from Simple Cycle to a Recompression Brayton Cycle (RCBC) configuration and operate up to 715°C. The modifications include adding a second compressor, a second recuperator, and a higher temperature turbine stop valve, which will improve thermal efficiency, increase mass flows and more than double the power output. This project is on-going and is making a significant contribution to the advancement of this promising power generation technology offering efficiency, cost, and emissions improvements over existing approaches.

NOMENCLATURE

CTS	= Cooling Tower System
CSP	= Concentrated Solar Power
DAP	= Data Acquisition Periods
DCS	= Distributed Control System
DGS	= Dry Gas Seal
FAT	= Factory Acceptance Test
GE V	= GE Vernova
GTI	= GTI Energy
JIP	= Joint Industry Program
IGV	= Inlet Guide Vanes
HTR	= High Temperature Recuperator
MW_e	= Electric Power in MW
MW_t	= Thermal Power in MW
ORC	= Organic Rankine Cycle
PCHE	= Printed Circuit Heat Exchanger
RCBC	= Recompression Brayton Cycle
sCO_2	= Supercritical Carbon Dioxide
SC	= Simple recuperated Brayton Cycle
SCR	= Selective Catalytic Reduction
SRBC	= Simple Recuperated Brayton Cycle
STEP	= Supercritical Transformational Electric Power
SwRI	= Southwest Research Institute
TCV	= Turbine Control Valve
TIT	= Turbine Inlet Temperature
TSV	= Turbine Stop Valve
WHR	= Waste Heat Recovery

INTRODUCTION

Supercritical carbon dioxide (sCO_2) power cycles utilise CO_2 as a working fluid to convert heat to power. They offer more compact turbomachinery, less water use and the potential for higher cycle efficiencies over other energy conversion technologies such as steam Rankine or Organic Rankine Cycles (ORC); especially when operating at elevated temperatures [1,2,3,4].

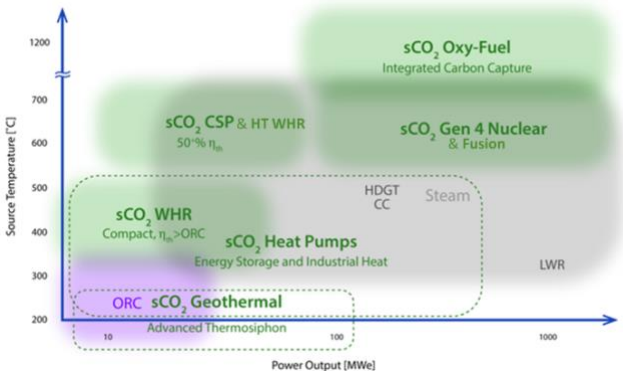

Figure 1: sCO_2 Power System Application Space Map.

The US Department of Energy (DOE), through its Solar, Nuclear, and Fossil Energy offices, sees the potential of this technology in its many applications

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which include gas and coal-fired power plants, bottoming cycles, industrial waste heat recovery (WHR), concentrated solar power (CSP), shipboard propulsion, biomass power plants, geothermal power, nuclear power (from both fission and fusion), and energy storage.

Figure 1 is an updated map of sCO2 applications as a function of power output and heat source temperature relative to incumbent steam and ORC power generation options (adapted from [2]).

Enabled by advancements in materials, manufacturing, and numerical modeling, the US DOE launched a comprehensive program of R&D projects more than ten years ago to advance component technologies and to demonstrate operation of integrated systems. This included a 1 MW_e power loop led by Southwest Research Institute (SwRI) which achieved the highest sCO2 turbine operating temperatures to date (715°C) and encouraged further validation at larger scales [5,6,7,8]. These efforts culminated in the current 10 MW_e STEP Demo pilot project which is demonstrating the operability and performance of the indirect-fired sCO_2 power cycle at a commercially-relevant scale.

STEP Demo pilot testing is occuring in two cycle configurations as shown in Figures 2 and 3.

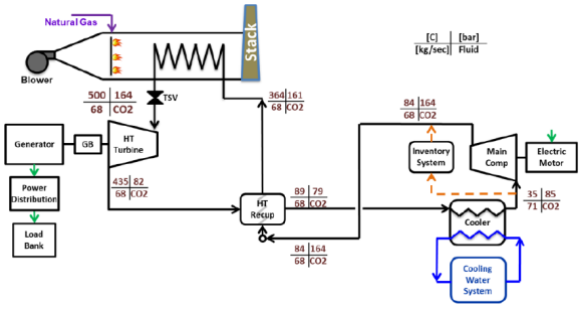

Figure 2: STEP Demo Simple Cycle Configuration.

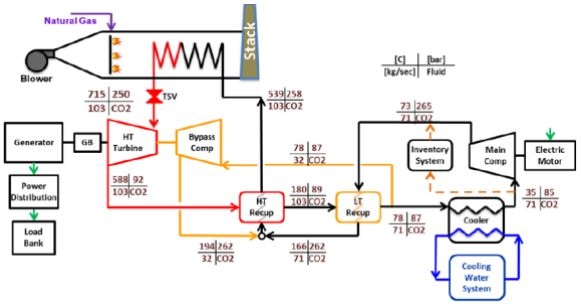

Figure 3: STEP Demo RCBC Configuration.

The initial system configuration was a Simple Recuperated Brayton Cycle (SRBC or SC) and these tests are now complete. The results of these tests are presented in this paper. It operated at turbine inlet temperature (TIT) of up to 500°C and a pressure of 206 bar. This configuration is relevant to waste heat recovery (WHR) applications for example from small simple-cycle gas turbines. The 715°C 250 bar RCBC configuration will demonstrate the highest efficiency potential achievable within the limits of state-of-the-art code approved materials and is applicable to high temperature applications including CSP, industrial heat recovery, and next-generation nuclear. At the time of paper writing, the pilot plant is being converted to this RCBC configuration.

GTI Energy leads this $170 million government-industry partnership, teaming with SwRI, GE Vernova Advanced Research (GE Vernova), and the U.S. DOE National Energy Technology Laboratory (NETL). This project is possible because of support from both public and private organizations and the project is grateful to its Joint Industry Partners (JIP members) including AEP (American Electric Power), CSIRO (Commonwealth Scientific and Industrial Research Organization), EGAT (Electric Generating Authority of Thailand), Engie, KEPCO (Korean Electric Power Company), NRCan (Natural Resources Canada), Petrobras, SCS (Southern Company Services), Spectrum, and the State of Texas (TCEQ). The project continues to actively welcome additional participants from the U.S. and internationally.

STEP DEMO PILOT PLANT OVERVIEW

The STEP Demo pilot plant was built on a greenfield site and included the construction of a dedicated 22,000ft^2 building located on SwRI's campus in San Antonio, Texas. Groundbreaking occurred in 2018, and mechanical completion was in October 2023 [9]. Inside and outside views of the plant are shown in Figures 4 and 5.

Figure 4: STEP Demo 10 MWe sCO2 Pilot Plant Inside View.

Figure 5: STEP Demo 10 MWe sCO2 Pilot Plant Outside View.

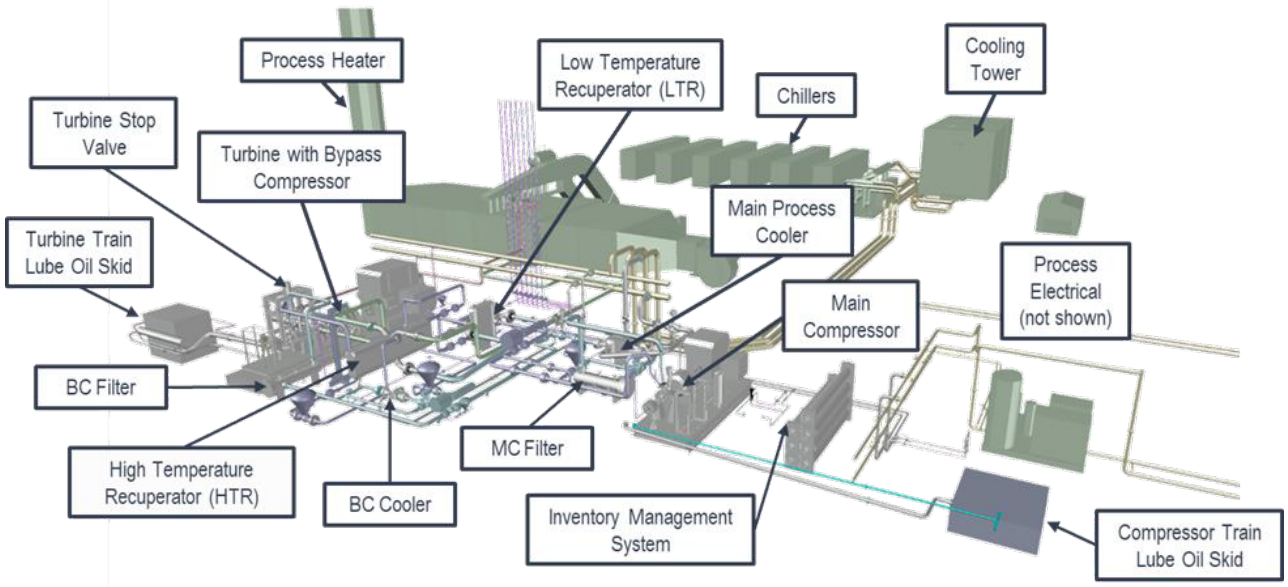

Figure 6: STEP Demo Pilot Plant Arrangement.

Figure 6 shows the general arrangement of the STEP Demo plant equipment. Key components include the 16 MW gross power turbine, a turbine control/stop valve, main and bypass compressors, an 80 MW_{th} natural gas-fired heater, a 25 MW_{th} cooling tower system with provision for 3,000 tons of auxiliary chilling, two recuperative heat exchangers, several cooling heat exchangers, a CO2 supply and inventory management system, electrical inter-connections for grid connected operation, load banks for island-mode operation, connecting piping, and a GE Mark VI distributed control system (DCS). High temperature components and piping were designed for 715°C and 250 bar operations in line with ASME code guidance applying superalloys (including Inconel® ALLOY 740H® and HAYNES® 282®) for the most extreme operating conditions. The STEP Demo facility has some of the largest components known to have been designed, built and operated with these materials. The main piping is 8" and 10" diameter 740H® and the lower temperature piping is of grade P91 (a high chrome steel). The design, fabrication and installation of STEP Demo pilot components and the plant has been extensively reported [9,10,11,12,13,14]

The turbine is 16 MW gross axial-type designed by SwRI and GE Vernova and is based on the predecessor 1 MW US DOE Sunshot project (DE-EE-0005804) which had the same turbine frame size but with a scaled gas path [5, 6]. The STEP Demo pilot sCO2 turbine is shown in Figure 7 and the design and fabrication have been reported in [15,16,17]. This turbine has the highest power density of any terrestrial turbine known at over 20,000 hp in a very small, compact package achieving approximately 100 hp/lb or 16 MW gross and weighing 80 kg. (Figure 7) [9,17].

A turbine stop and control valve placed upstream of the turbine is used to throttle flow for load control and is designed to close within 200 ms to protect the turbine

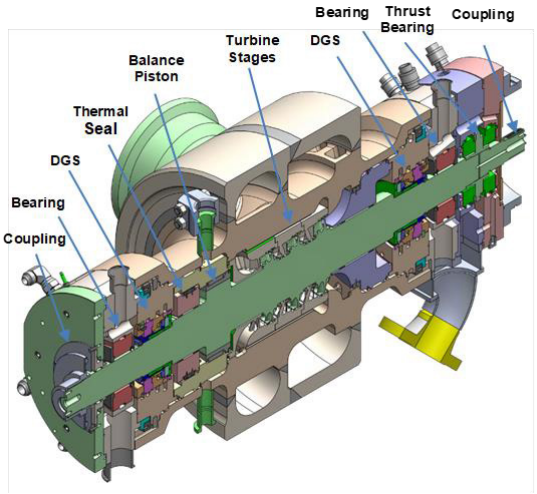

Figure 7: Isometric View of STEP Demo 16 MW Gross sCO2 Turbine Expander [9, 17].

from overspeed in the event of a trip and loss of generator load. The original high temperature (715°C capable) valve was based on an existing GE commercial product line of steam valves with a body material substitution to cast HAYNES® 282® but has proven to be difficult to manufacture. An alternate valve made of 316 stainless steel was procured from AVS Hora and was operated during simple cycle testing up to 500°C. A high temperature valve has been designed and is being manufactured with a machined Inconel® 740H® body by SchuF, to enable the planned test operations up to 715°C.

The main and the bypass compressor systems are provided by Baker Hughes and leverage their existing commercial product line as well as work undertaken in the DOE DE-EE0007109 APOLLO program [20,21]. APOLLO evaluated and modeled compressor performance near the CO2 critical point. Compressor design and operation near the dome is very challenging due to the wide range of flow and pressures required, the need for start-up in two phase conditions, and operation

close to the critical point where fluid properties change rapidly.

Other equipment of note includes heat exchangers (recuperators and coolers) which are compact PCHE-type (printed circuit heat exchanger) and are supplied by Heatric and VPE.

SIMPLE CYCLE OPERATIONS

Mechanical completion occurred in October 2023 and is reported in [9,10]. The commissioning of the turbine skid is described in detail in [18,19]. The part of the loop associated with the compressor, including the main process cooler, filter, recycle loop, valve, and orifice lines were completed first allowing for first spin and mapping of the compressor only. The whole plant was subsequently operated with first spin of the turbine being achieved in December 2023.

The turbine break-in followed a gentle run-in procedure for the abradable labyrinth seals. A low TIT (~200°C) achieved by running the heater with a reduced flow (~30%) through the turbine warmed the loop and vaporized liquid CO_2 during cold start of the plant. This start up procedure allowed the proper CO2 mass levels to be filled while raising the system temperatures and pressures. Achieving supercritical conditions prior to starting the turbine prevented damage to the turbomachinery due to potential liquid slugging. The speed was gradually increased, first to an idle speed of 12,000 rpm and then increased as the TIT was increased reaching full speed at approximately 300°C. Speed control of the turbine is managed by feedback to the Turbine Control Valve (TCV).

Initial testing was performed by energizing the generator and loading it (via load banks) leading to the targeted temperature of 500°C TIT at Simple Cycle Minimum Load (‘Simple-Min’) conditions. ‘Simple-Min’ (~40% load) was obtained by reducing compressor speed to a minimum value of 20,700 rpm and closing the IGVs (Inlet Guide Vanes) to their minimum value of –70°. Grid synchronization of the generator was then achieved, which helped control turbine speed and permitted full opening of the TCV. The mass flow was increased to its maximum value at full compressor speed and +10° IGV setting (defined as ‘Simple-Max’ condition). A summary of these conditions is shown in Table 1.

Table 1: Simple Cycle Operating Conditions for Turbine.

Parameter	‘Simple-Min’	‘Simple-Max’
Speed	20,700 rpm	26,620 rpm
Inlet/Exit Pressure	164/93 bar	206/94 bar
Inlet Temperature	500°C	500°C

Table 2 shows the progression through the test plan along with power achieved and trips experienced. One trip was encountered due to excessive gearbox vibration, but after reviewing the data with the gearbox manufacturer, the trip control system levels were increased to account for the higher vibration until the gearbox is sufficiently loaded due to idler gear oil whip.

Table 2: High-Level Summary of STEP Demo Pilot Simple Cycle Testing and Operations.

Goal	Max Power	Trip Events Encountered
Turbine at full speed and high temperature with low load	100 kWe on Load Banks	N/A
500°C TIT with Load Banks	150 kWe on Load Banks	N/A
Ammonia injection in the heater for emissions reduction	290 kWe on Load Banks	Turbine Gearbox vibrations
Achieve ‘Simple-Min’	2.6 MWe on Load Banks	Generator overvoltage
Grid Synchronize	1.1 MWe export to Grid	No current measured on bus
Achieve ‘Simple- Max’	8.3 MW aero, 7.4 MWe generator, 3.9 MWe export to Grid	N/A
Emission Testing at ‘Simple-Max’, Repeat Simple Min	3.9 MWe gross power to Grid	N/A

A second trip was encountered due to a generator over-voltage, which was caused by a control system error that was quickly corrected. A third trip was due to loss of electric current measured on the generator bus caused by a short in a current transformer that resulted in a full-speed and loaded fast-stop to prevent overspeed. This issue was quickly identified and corrected allowing the test matrix to be completed achieving ‘Simple-Max’ conditions with a gross aerodynamic power from the turbine of 8.3 MW and an electrical power at the generator terminals of 7.4 MW_e. Subtracting the compressor VFD power yielded a net plant output of 3.9 MW_e at ‘Simple-Max’ conditions. Lastly, an emissions test was performed consisting of a 6-hour run at ‘Simple-Max’ conditions with emissions sampling of the stack flue gases. The results showed good performance from the SCR with NOx emissions well below environmental permit limits and minimal ammonia slip.

The measured TIT over the SC test campaigns is given in Figure 8. A two-week downtime was required to correct some wiring issues with the main switchgear and transformer.

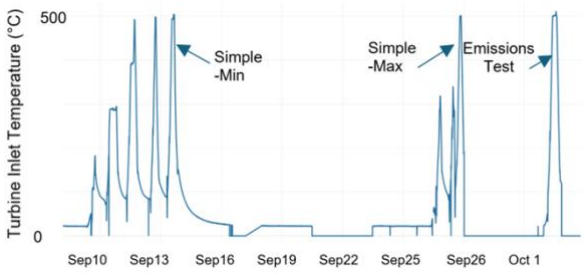

Figure 8: STEP Demo Pilot Simple Cycle Test Campaigns in September and October 2024 [19].

Figure 9 provides the compressor and turbine speed along with their respective inlet temperatures. Stable plant operation was demonstrated during the 6-hour emission test with grid synchronization and stable turbine speed, and with good process heater and main cooler temperature control. After the emissions test was complete, the plant turn-down to 'Simple-min' conditions was repeated by slowing the compressor and closing the IGVs as shown in Figure 9. Once performance data was captured, the TIT was ramped down and the equipment was stopped in a well-controlled manner without any trips. Overall operability and control was very good. It should be noted that these tests did not attempt to verify fastest ramp rates which will be a future investigation since the project team did not now want to harm any components. Operational knowledge about how to operate an sCO_2 power plant was gained, such as: turbine start-up, loop mass control, emergency trips, and grid synchronization. This knowledge will be impactful for the RCBC configuration testing.

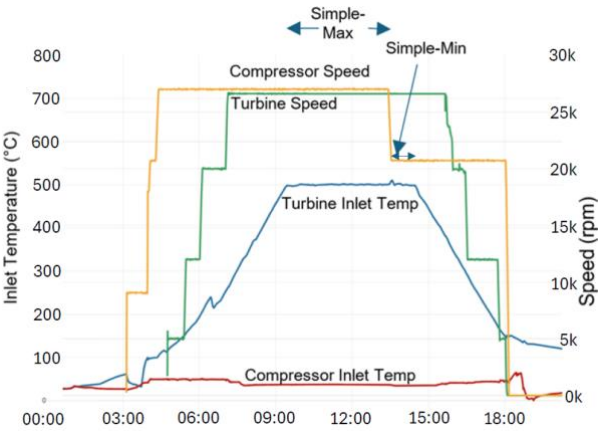

Figure 9: Operating Conditions During the 6-Hour Emissions Test [19].

OVERALL PLANT PERFORMANCE

Measured cycle performance was compared to the predicted cycle performance using bar and 45-degree charts as shown in Figures 10–13. The Data Acquisition Periods (DAPs) representing the 'Simple-Max' and 'Simple-Min' conditions are located in the positive region of the plots, whereas the DAPs selected from intermediate ramp-up time slices yield negative power outputs and efficiencies due to the main components not reaching their designated setpoints.

Measured cycle aero power outputs and aero efficiencies for 'Simple-Max' and 'Simple-Min' conditions are up to 13% lower than their predicted values (Figure 12 and 13). Note that aero power is just the power from the turbine while net efficiency includes other losses of the overall plant such as compression energy. Model refinement for all loses in still in work.

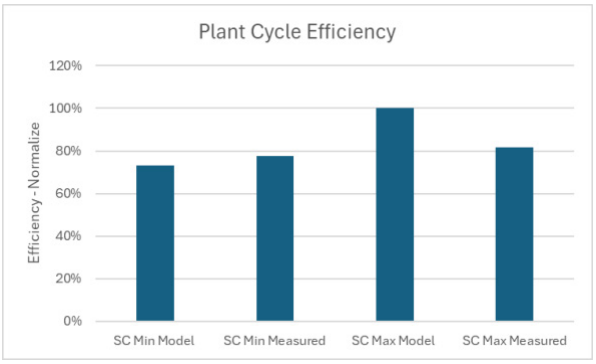

Figure 10: Normalized Plant Cycle Efficiency, Measured vs Model.

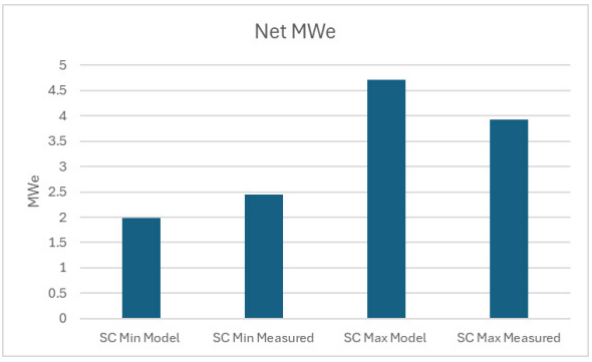

Figure 11: Net MW_e, Measured vs Model.

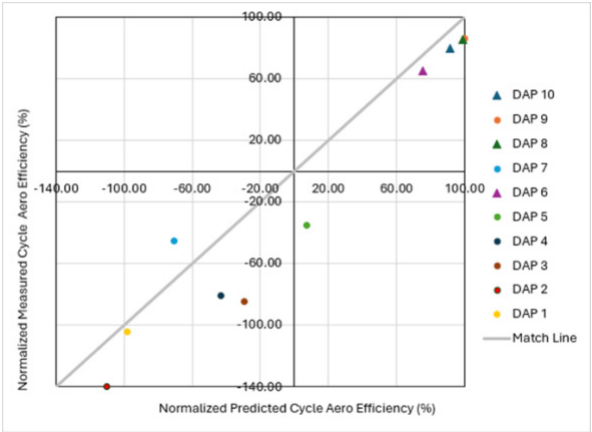

Figure 12: 45°-plot of Normalized Aero Efficiency, Measured vs Model.

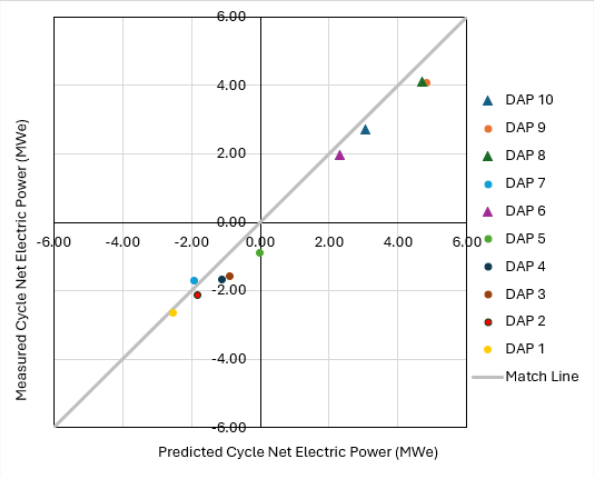

Figure 13: 45°-plot of Net MW_e, Measured vs Model.

The predicted performance for other components was better, for example Figure 14 shows the measured vs predicted performance of the High Temperature Recuperator (HTR).

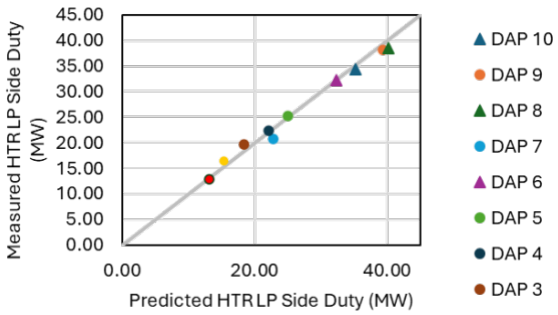

Figure 14: 45°-plot of HTR LP Side Duty, Measured vs. Predicted.

TURBINE OPERATION

The STEP Demo Pilot turbine train is shown in Figure 15 and its monolithic rotor is shown in Figure 16. Figure 17 provides the measured turbine efficiency (normalized by the peak predicted efficiency) compared to the predicted value given at the same conditions on the 45-degree chart. Measured efficiencies were up to 4% lower than predicted for some operating points. However, the measured efficiency is expected to be lower in this case, since the predicted efficiency equation does not yet include updated inlet and exit plenum losses in the turbine, while the measured efficiency is a flange-to-flange efficiency. Future work will update the efficiency prediction equation to include the updates to inlet and exit losses, which will result in closer matching between measurement and prediction.

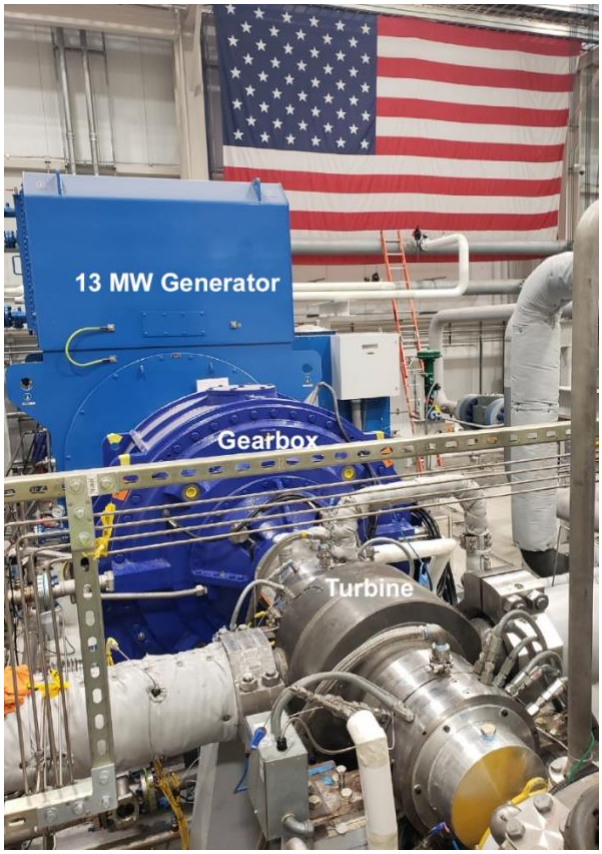

Figure 15: sCO2 STEP Demo Turbine Train (16 MW_e gross).

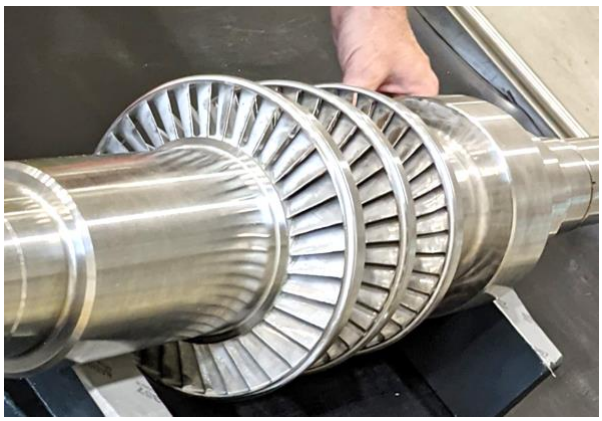

Figure 16: Close-up of STEP Demo Pilot Turbine Rotor.

The results reflect the turbine operating below its best efficiency point, which is expected to be improved when the additional mass flow from the bypass compressor is included during RCBC testing. The net plant output will also further increase as the compressor is operating closer to its best efficiency point and the TIT is increased to its design value of 715°C.

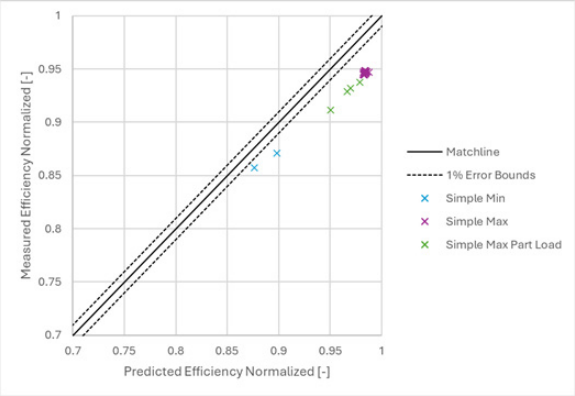

Figure 17: Normalized Turbine Efficiency, Measured vs. Predicted [19].

COMPRESSOR OPERATION

The main compressor (Figure 18), is a 2.7 MW single stage centrifugal compressor, operating up to 27,000 rpm driven through a gearbox by an electric motor with a variable frequency drive. It is designed to operate at supercritical conditions as well as being capable of operating in multi-phase conditions. The ability to operate with liquid is important to support cool restart conditions.

The main compressor loop was successfully commissioned in August 2023, and performance maps of the compressor were developed [22]. 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 34.6°C to 45°C.

Figure 18: Main Compressor in Skid-Mounted Package.

The actual performance maps were found to be different than the maps from the FAT (Factory Acceptance Test), with significantly less turndown than expected. Turndown (max flow/min flow) reduced by approximately a factor of two relative to pretest projections. However, the compressor was still able, to achieve target performance regarding pressure and flow for the RCBC design point and for the SC test conditions. Further work is needed to understand what is causing these differences and how to resolve them in future applications.

PLANT CONTROL AND SIMULATION

A dynamic simulation model has been developed by GTI Energy utilizing Flownex® Simulation Environment (Flownex SE) to model the STEP Demo pilot [23,24]. Static and dynamic models for both the Simple Recuperated Brayton Cycle (Simple Cycle) and Recompression Brayton Cycle (RCBC) configurations have been created.

Transient simulations completed include startup, shutdown, load level changes, and trips. Control loop algorithms have been incorporated in the model to help determine adequate control methodologies for the test facility. Additionally, the dynamic model is being incorporated into a plant simulator that operators can be trained with.

Following simple cycle testing, the Flownex model compressor maps were updated using measured performance data which reduced the discrepancy between predicted and measured compressor power from 20% to approximately 3%. Measured cycle aero power outputs and aero efficiencies for ‘Simple-Max’ and ‘Simple-Min’ conditions initially showed discrepancies of up to 25% from their predicted values in Flownex. Adjustments to key input parameters, including turbine inlet temperature, compressor inlet conditions, generator and gearbox efficiencies, along with the integration of updated compressor maps derived from test data, reduced these discrepancies to approximately 13%.

Figures 19–21 show the shutdown sequence system results, as measured and as predicted, for turbine and compressor speed (Figure 19), system pressures (Figure 20) and system temperatures (Figure 21). The system responses were generated by inputting the shutdown sequence into the transient model and were evaluated against component and operational limitations. This simulation verifies all requirements are satisfied with the current model assumptions and inputs. This simulation will be rerun and reevaluated as test validated inputs are incorporated into the dynamic model.

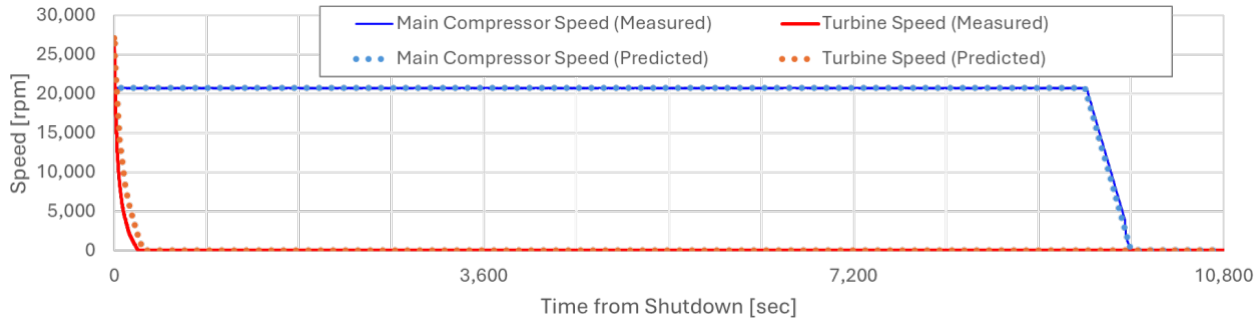

Figure 19: Measured and Predicted Turbine and Compressor Speeds in Controlled Shutdown.

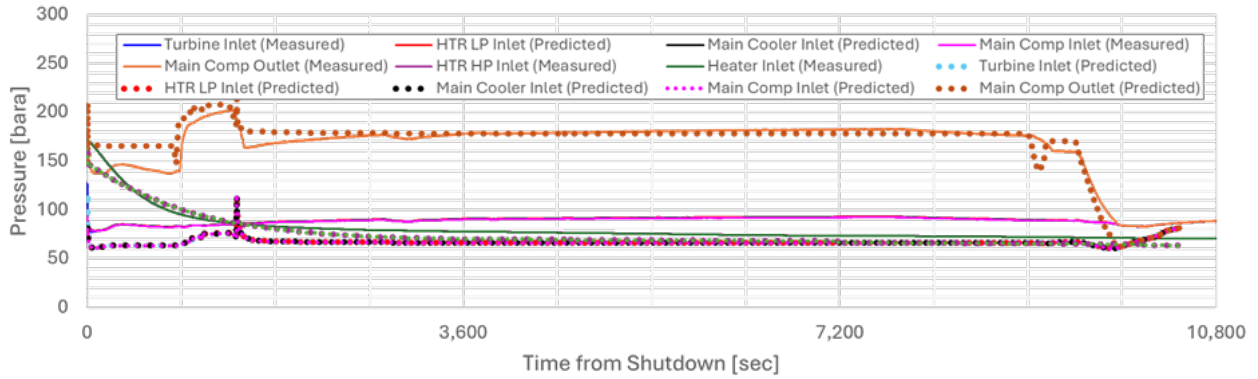

Figure 20: Measured and Predicted System Pressures in Controlled Shutdown.

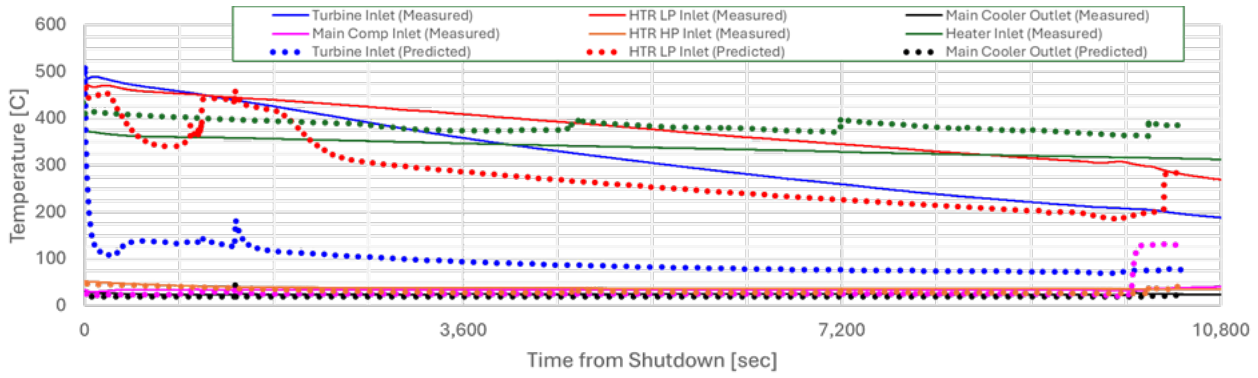

Figure 21: Measured and Predicted System Temperatures in Controlled Shutdown.

NEXT STEPS – RCBC CONFIGURATION

The project is currently in Budget Period 3 (BP3) in which the pilot is being transformed from the SC to the RCBC configuration, and will be operated with a TIT up to 715°C. The modifications include adding a second compressor, a second recuperator, and a higher temperature TSV, all of which will improve power cycle thermal efficiency, increase mass flows, and more than double the power output.

NEXT STEPS – sCO2 COMMERCIALIZATION

The STEP Demo project is making a significant contribution to the advancement of and the commercial readiness of sCO2 power systems. At a scale of 10 MWe net, the plant and its components are already at a commercial scale and the testing is validating design and operations understandings, as well as capturing valuable lessons learned. Our commercial partner, GE Vernova, and our key component suppliers, including Baker Hughes, Heatric, Optimus, and others such as the valve suppliers are all gaining confidence through this project to be able to offer components commercially. The STEP project team believes market development to first be for waste heat recovery applications and secondly for advanced nuclear such as SMR's, CSP, and thermal-electric storage applications. Initially, some of these applications are likely to be at the scale similar to the STEP Demo pilot, but further scale-up is also expected which will require manufacturing and construction optimizations. Examples include a transition from a monolithic turbine shaft and blades to a more traditional approach of dove-tailed blades on the turbine disk. Also, limits in shipping and construction are likely to drive heat exchangers to be more modular with multiple parallel units.

The STEP Demo pilot is expected to be a valuable resource for further component validation and cycle configuration testing, and potentially FAT for commercial order fulfilment since this facility has unique capabilities for high pressure and temperature sCO_2 that is not available elsewhere. The original plan for the STEP project was to include a cascade cycle in addition to the SC and RCBC configurations that are being tested. Also, longer duration tests (>1,000 hours) were envisioned to gain equipment reliability confidence, but is currently not planned due to budget constraints. All of these are possible with interest and funding support. Historically, new power plant technologies have been enabled by "launch customers" to host and bear costs through revenues generated, while risks are mitigated by grant support and pre-commercial terms from commercial suppliers which might include limited performance and delivery guarantees, as well as services and parts availability over a defined plant life. These supporting aspects will likely be required to move sCO_2 power from the STEP project to full commercial deployment.

CONCLUSIONS

The STEP project achieved a major industry milestone by completing the Simple Cycle test plan including operation at 500°C, 206 bar and 93 kg/s mass flow, generating 8.3 MW turbine aero power and 3.9 MWe net electric power, all while grid synchronized. The mechanical performance including bearing temperatures and vibrations were well within limits. No dry gas seal (DGS) failures were encountered on the turbine demonstrating good thermal management and seal gas supply cleanliness. One main compressor DGS failure was experienced due contamination early in commissioning. The heater and recuperator heat exchangers showed excellent performance close to predictions.

The plant is currently undergoing modification to the RCBC configuration, which will increase cycle efficiency, increase TIT, and increase mass flow due to the addition of the bypass compressor. The net results of these modifications should more than double the power output of the plant and greatly improve the cycle efficiency and the operation of the equipment closer their optimum conditions.

Supercritical CO2 power cycles show great promise to improve powerplant output and efficiency and are a good match for solar thermal, nuclear, waste heat recovery, and geothermal heat sources. The STEP project is helping to retire many of the risks associated with this technology and is informing the supply chain for the critical equipment. The project is open to interested parties through a Joint Industry Program, and once the current project is complete, the facility is available to serve the international research and development needs of this growing market segment.

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DISCLAIMER

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