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SCO2 POWER CYCLE DEVELOPMENT, MODELING AND DEMONSTRATION AT STEP

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ABSTRACT

The paper will focus on the 10 MWe Supercritical Transformational Electric Power (STEP) Pilot Facility and the important role that computer modeling and simulation has played in the design and will play in the facility operation.

The STEP Demo project team is led by the Gas Technology Institute (GTI), in collaboration with Southwest Research Institute, and General Electric Global Research (GE-GR), and the U.S. Department of Energy. The team is executing a project to design, construct, commission, and operate an integrated and reconfigurable 10 MWe sCO_2 Pilot Plant Test Facility located in San Antonio, Texas. This project is a significant step toward commercialization of sCO_2 cycle power generation and will demonstrate performance and operability needed for scale-up to commercial facilities. The pilot plant is currently under construction, with commissioning activities to start in the first quarter of 2022. By the end of this seven-year project the operability of the sCO_2 power cycle will be demonstrated and documented starting with a simple recuperated cycle configuration initially operating at a 500 °C (932 °F turbine inlet temperature and progressing to a recompression closed Brayton cycle technology (RCBC) configuration operating at 715 °C (1319 °F).

INTRODUCTION

Supercritical CO_2 (sCO_2) Brayton power cycles use supercritical CO_2 as the working fluid, converting heat to power. They are expected to provide higher system efficiencies than other energy conversion technologies such as steam Rankine or Organic Rankine cycles; especially when operating at elevated temperatures. sCO_2 power cycles are being evaluated, and system studies performed for a wide range of applications including fossil-fired systems, waste heat recovery, concentrated solar power, and nuclear power generation.

Figure 1 – STEP team members in front of new high bay

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 STEPDemo is a significant scale-up (to 10 MWe) of a fully integrated and functional electric power plant (Figure 1). The STEPDemo 10 MWe pilot project is demonstrating indirect fired sCO_2 cycles to known available materials limits (T>700°C). The project will enable the progression of technology readiness level from TRL3 to TRL7 and subsequent commercialization. The project is well underway and commissioning in expected in 2022.

The project has also made a significant investment in computer modeling of the STEP facility sCO$_2$ systems to support design decisions and operational planning. Steady state models were used to establish primary component specifications, auxiliary system requirements and pipe sizing. Dynamic models are used to verify time-sensitive operations like start-up, load changes, trip procedures, control logic, and component interactions. These transient simulations are a key part of operational planning. As data is generated during commissioning and test operations the model results will be compared against the data to improve the models for future use. Validating the models will create a powerful tool for future sCO$_2$ plant design.

Several technical risks and challenges will be mitigated in this STEP Demo project:

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

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STEP PROJECT OBJECTIVES

The STEP project has an agreed upon set of objectives that will be accomplished before project end.

- Demonstrate the operability of the Supercritical Carbon Dioxide (sCO$_2$) power cycle.
- Verify the performance of components including turbine elements, compression systems, and recuperators.
- Demonstrate the potential for producing a lower cost of electricity in relevant applications.
- Demonstrate 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).
- Demonstrate a $\geq$ 700 °C turbine inlet temperature.
- Validate 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.
- Complete a reconfigurable facility to accommodate future testing that accommodates:
  - 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).

STEP PROJECT SCOPE

Testing will occur in two configurations as shown in Figure 2. The initial system configuration will be the sCO$_2$ Simple Cycle operated at turbine inlet temperature of 500°C and 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 to 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 from small simple cycle gas turbines, for example.

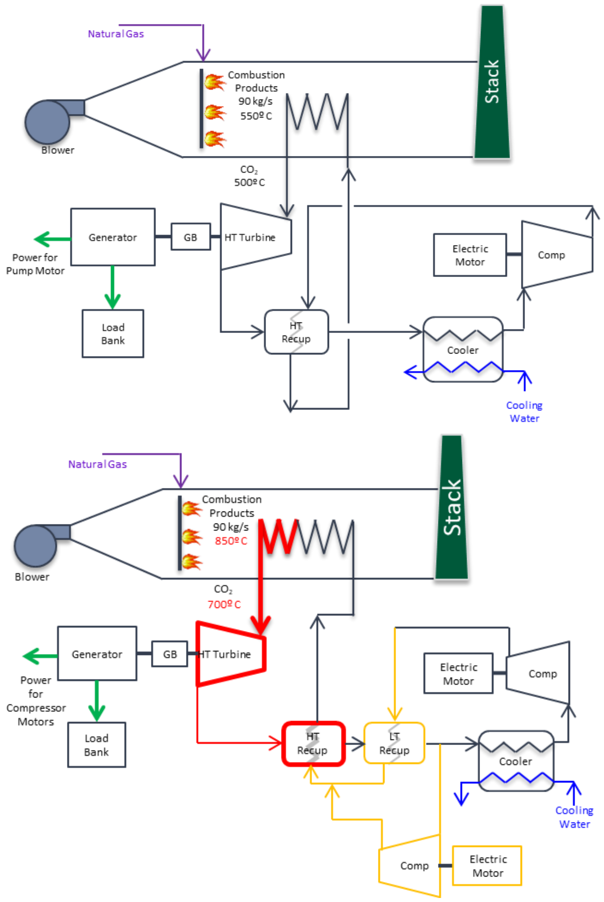


Figure 2 Simple Cycle (top) and RCBC (bottom) configurations

The second configuration is the Recompression Brayton Cycle (RCBC) which increases complexity but leads to higher efficiency. The RCBC adds a bypass loop adding another compressor, recuperator, and cooler to optimize the cycle performance. The RCBC configuration will deliver over 100 kg/s of CO_2 at 700°C to the turbine at 250 bar at the design point. The main compressor handles about 70 kg/s and the bypass compressor about 30 kg/s. The RCBC will allow testing to determine the full capability of the sCO_2 system.

JOINT INDUSTRY PROGRAM

A Joint Industry Program (JIP) team has been formed by the STEP Project Team with industry partners interested in the proliferation of this technology. The JIP has multiple partners who provide both funding and technical guidance to the STEP Demo project. The JIP includes a Steering Committee with the U.S. DOE, project partners GTI, GE, and SwRI, and funding members including American Electric Power, Southern Company Services, Electrical Generation Authority for Thailand (EGAT), Engie, Korean Electric Power Company, Natural Resources Canada, Commonwealth Scientific and Industrial Research Organization (Australia), and the state of Texas via the Texas Commission on Environmental Quality or TCEQ. The JIP continues to be open to interested parties.

SCHEDULE

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

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 2022)

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

BUDGET PERIOD 3 - (forecast to end in 2023)

- Facility Operation and Testing
- Facility reconfiguration
- Test recompression cycle

STEP 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 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. All major equipment is in fabrication or already delivered to site. Large-scale fabrication efforts have already provided valuable project learnings for technology commercialization. These have been documented in previous progress reports in “Marion et al. (2019)”, “Marion et al, (2020)”.

The Test Facility

The STEP Pilot Plant is housed in a new 22,000 ft2 General-Purpose Test Facility [GPTF] located on SwRI’s campus in San Antonio, Texas (Figures 3 and 4). The building received a certification of occupancy in June 2020. The facility provides the infrastructure to support 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 for first article acceptance or variable speed performance mapping. Primary heater and cooling system are installed, and process hardware is being installed (compressors, generator) in the high bay.

Figure 3 – Side view of SwRI GPTF building March 2020

Equipment Arrangement

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 4, and 5.

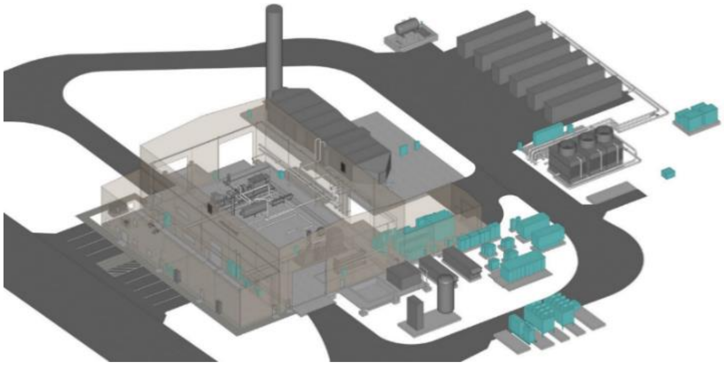


Figure 4. STEP facility site layout

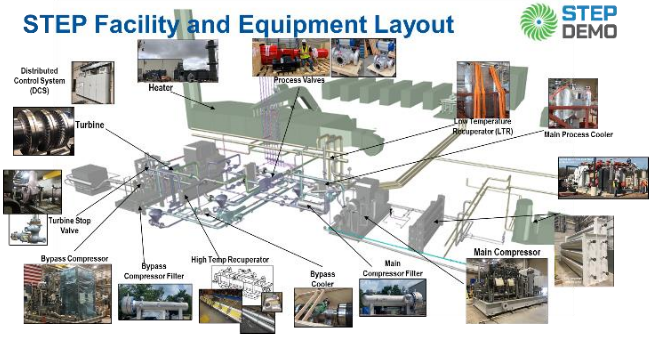


Figure 5 – 10 MWe STEP pilot power plant equipment arrangement

Turbine

The STEP turbine is 16 MW_{th}. The design (cross-section view shown on Figure 6) is based on the previously tested SunShot project turbine. SwRI and GE fabricated and successfully tested it to 715°C and 27,000 rpm (“Kalra et al. (2014), “Moore, et al. (2018)). The SunShot turbine design was updated by the STEP project to increase rotor life (100,000 hrs. from 20,000 hrs.), add shear ring retention instead of bolts, add couplings on both ends of the shaft, and optimize volute flow area to increase aerodynamic performance. SunShot testing results “Moore et al (2018)” and design enhancements developed under a related ARPA-E program (DoE Advanced Research Projects Award (2014)) were used to improve the design of the thermal management region.

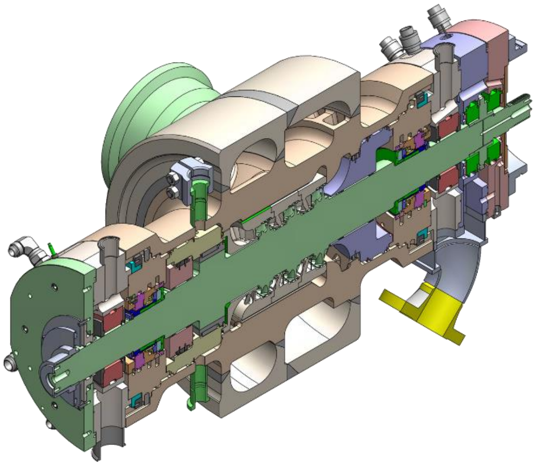


Figure 6 - 10 MWe STEP sCO_2 turbine

Turbine Manufacturing

The engineering design of turbine and compressors is made more difficult by the STEP system cycle configuration. This led to a small diameter internals within the case of the turbine for its length. New fabrication techniques were developed by Baker Hughes that provide the capability to produce small compressor rotors, using a 5-axis EDM machine. This allows machine tools to reach within the case to manufacture the tight tolerances required for the monolithic STEP turbine rotor.

Turbine Stop and Control Valve

A special valve was designed for turbine flow control and emergency flow shutoff (Figure 7). In an emergency shutdown, the valve will close in under two tenths of a second. The GE Power commercial steam turbine uses a similar design that was changed to accommodate higher temperature and the CO_2 environment.

There are several differences in the design of this STEP valve from the GE steam valve.

1. Haynes 282 high temperature nickel alloy material is used. The material data used comes from the AUSC steam power development for high temperature, high-pressure materials, and components, “Marion et al. (2014)”.
2. High fidelity CFD was used as part of the design process model sCO_2 (as opposed to lower density steam) flow and pressures within the valve.
3. Improved seals for the stem.
4. This design of compact self-contained actuators is leveraged from commercial designs used by Baker Hughes. This is a better match to the compact nature of the sCO_2 turbomachinery.

Figure 7 - Turbine stop valve and body casting

Compressor

The designs of the compressors are based on Baker Hughes commercial units. Input was also provided by lessons learned during the DOE-funded APOLLO program, “DoE Concentrating Solar Power (2019)”. The design of the compressor rotors (Figure 8) uses a monolithic design that works well for the small size impellers in this compact sCO_2 power cycle. The main and bypass compressors rotors were fabricated by a 5-axis EDM machine in Baker Hughes Florence, Italy shops. Then the compressors were assembled, factory acceptance testing [FAT], and installed at site.

Figure 8 – STEP main compressor monolithic rotor

Process Heater

In the STEP power system cycle sCO_2 is heated by natural gas. The heater has a tube bundle, headers and piping made of Inconel 740H due to the high temperature >700°C, 250 bar sCO_2 conditions. The design is similar to a duct-fired Heat Recovery Steam Generator (HRSG). Tube welding required special efforts to satisfy ASME PV guidance and certification. Extensive QA/QC inspection including hydrostatic testing was performed. The heater has been delivered to the test site in ten modules and assembled.

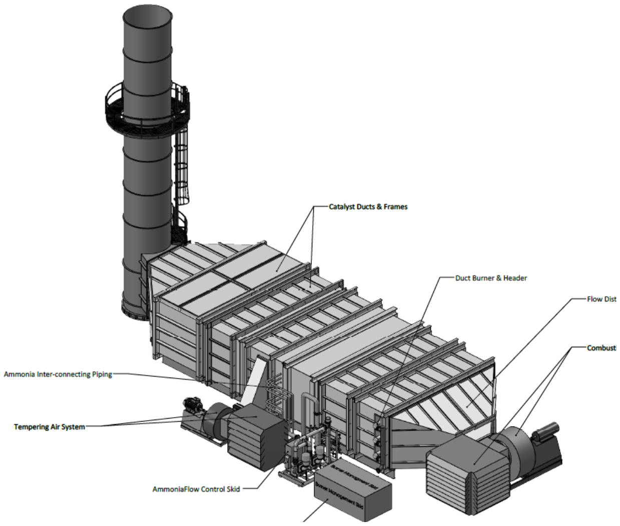


Figure 9 - Gas fired heater has 740H material for 715°C sCO_2

Recuperators

High performance, cost effective, heat exchangers are critical to the performance and economics of sCO_2 power cycles. As compared to a steam cycle, 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 the main heat exchangers for STEP pilot are compact printed circuit-type designs.

To date, the lower temperature heat exchangers (150 °C and 250°C duty) have been built and two of three received at the site; Figures 10 and 11.

Figure 10 Compact LTR sCO_2 recuperator delivered to facility

Figure 11 – PCHE type main cooler

The High Temperature Recuperator (Figure 12) operates with hot inlet flow of 600°C coming downstream 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 40 tons.

Modeling

All steady state and transient system performance modeling has been performed with Aspen and Flownex software. The property method used for both is NIST REFPROP. Aspen is the current industry standard software for steady state thermodynamic performance modeling and Flownex is an ISO 9001:2008 certified thermal-fluid platform with strong transient capability in supercritical CO_2 applications.

Figure 12 – HTR core assembly (joining of 10 separate PCHE blocks)

Initial steady state modeling was performed in Aspen Plus. Results are shown in Figure 13. There were 2 simple cycle cases and 7 RCBC cases. These results were used to define equipment requirements and specifications. As equipment steady state performance predictions were received from vendors, updates to the steady state models were made to ensure accurate performance prediction. This included use of main and bypass compressor factory performance maps. Custom recuperator models were built in Flownex for the transient analysis that incorporated vendor geometry. Tailored heat transfer correlations were also input. Since these custom models better predicted recuperator performance than the generic heat exchanger models in Aspen, updates to the steady state cases were made in Flownex. For this project, Aspen was better suited to define equipment requirements, whereas Flownex is better used to predict vendor equipment performance.

In addition to steady state modeling, Flownex is used for transient analysis of the STEP facility. Various transient operation cases have been evaluated, such as startup, trips, normal shutdown, and load level changes for both Simple Cycle and RCBC configurations. These results aid in determining the best sequencing of valve openings/closures and setpoints as well as ensuring adequate control of the facility. Other results aid in determining system requirements; for example, settle out conditions from the trip cases dictated low side pressure requirements.

An example of the results seen from the transient analysis is shown. Graphs from the Simple Cycle load level change transient are shown in Figures 14-16. This transient demonstrates the loop going from the Simple Cycle maximum load case to the simple cycle minimum load case (40% power) by throttling the turbine stop valve. Figure 14 shows the overall system temperatures with a heater controller maintaining a turbine inlet temperature set point of 500°C. Figure 15 shows the valve openings with the turbine stop valve (TSV) going from full open to 17% closed for the 40% power level and back to full opening for the max power load case. Figure 16 shows the system performance results throughout the transient. These results show overall performance of the loop and provide guidance on the impact on the system through the change of various parameters.

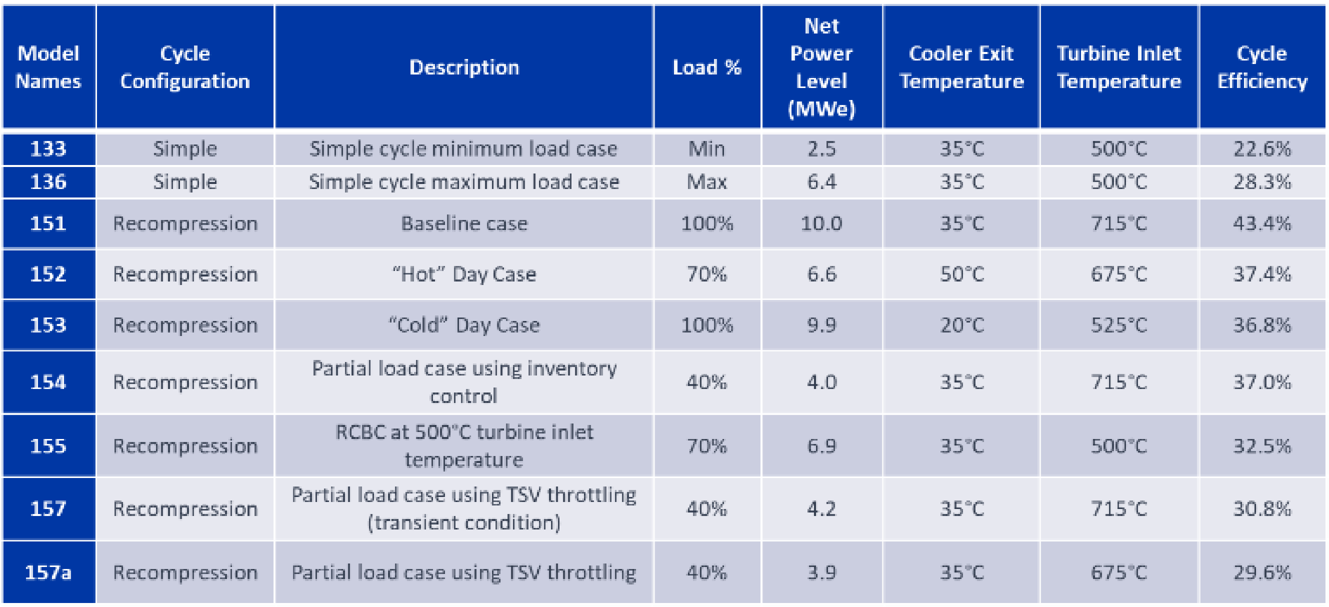
The system dynamic modelling has resulted in increased understanding of how to operate the STEP system. Some of the key findings are:

- The sequencing and timing of valve openings during start-up was evaluated and determined.
- How to assure that component temperature limits are not exceeded was found
- Determining when the minimum heater flowrate can be reached to enable heater ignition/firing.
- Determining if liquid formation occurs during loop filling.
- For RCBC, how to start up and connect the two parallel loops.
- For fast ramp scenarios, identifying other limiting steps (e.g., liquid vaporizer capacity).

As part of the STEP project, data generated will be used to validate the system steady state and dynamic models which will be used to project performance at commercial scale. These models will then be powerful tools for the design of other sCO_2 systems in the future.

Simulator

A simulator of the test facility will be built. The Flownex transient model will be used to represent the physics of the hardware. This simulator will be separate from the rest of the facility. The model will tie into a virtual controller in which will real time process data and control system data will be passed between the two. A simulator executive code will control the process model and virtual controller to ensure that the two are run time synched. The virtual controller will also tie to a human machine interface (HMI), which will mimic the data control system of the facility. Real time process data and control system data will be passed between the virtual controller and the HMI. A simplified schematic of the simulator is shown below in Figure 17. Operators will use this simulator for training and ‘what if’ scenarios to gain familiarity with loop system dynamics as well as practice various control strategies.



Model Names	Cycle Configuration	Description	Load %	Net Power Level (MWe)	Cooler Exit Temperature	Turbine Inlet Temperature	Cycle Efficiency
133	Simple	Simple cycle minimum load case	Min	2.5	35°C	500°C	22.6%
136	Simple	Simple cycle maximum load case	Max	6.4	35°C	500°C	28.3%
151	Recompression	Baseline case	100%	10.0	35°C	715°C	43.4%
152	Recompression	“Hot” Day Case	70%	6.6	50°C	675°C	37.4%
153	Recompression	“Cold” Day Case	100%	9.9	20°C	525°C	36.8%
154	Recompression	Partial load case using inventory control	40%	4.0	35°C	715°C	37.0%
155	Recompression	RCBC at 500°C turbine inlet temperature	70%	6.9	35°C	500°C	32.5%
157	Recompression	Partial load case using TSV throttling (transient condition)	40%	4.2	35°C	715°C	30.8%
157a	Recompression	Partial load case using TSV throttling	40%	3.9	35°C	675°C	29.6%

Figure 13 – Initial steady state results

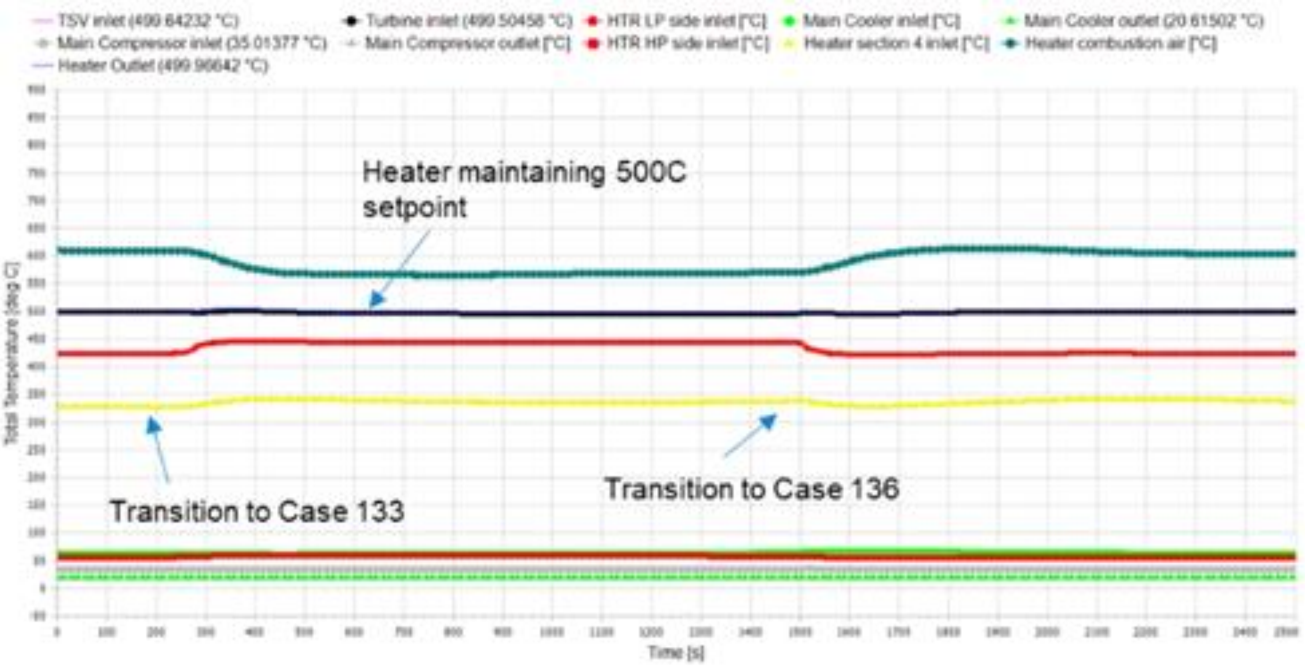


Figure 14 – Simple cycle load level change: system temperature

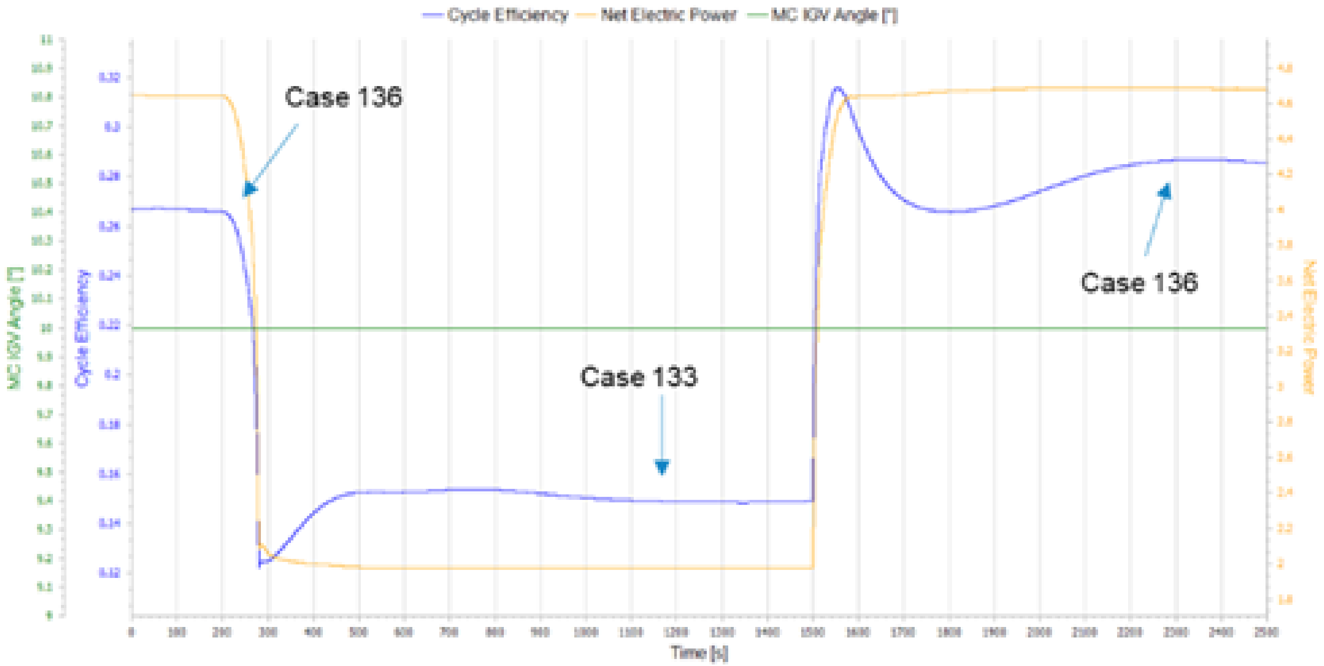


Figure 15 – Simple cycle load level change: valve openings

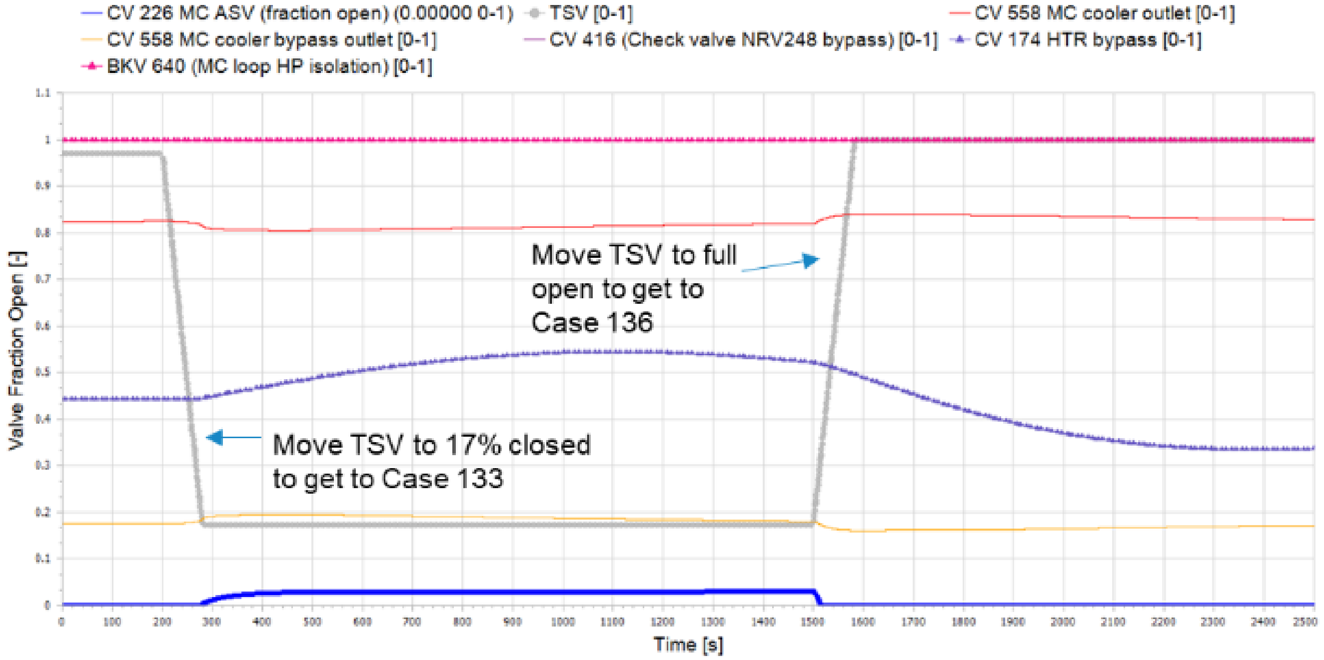


Figure 16 – Simple cycle load level change: system performance

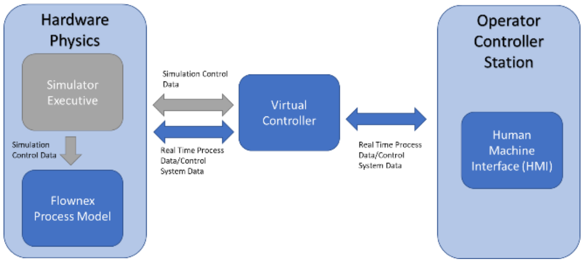


Figure 17 - Simplified schematic of the STEP simulator

Test Plans

Commissioning is planned to start in early 2022, based on current equipment fabrication, delivery, and installation plans. A program of parametric testing in simple cycle mode with a turbine inlet temperature under 500°C will be conducted shortly thereafter and into early 2022. Subsequently, the pilot will be reconfigured in Recompression Closed Brayton Cycle mode and tested in 2022 and 2023. The transient analysis will also be used as part of test planning. Parameter changes and setpoints can be input to the model to determine safe operating states and system control. Parameter sequencing can be tested in the model prior to actual testing.

SUMMARY

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

The STEP 10 MWe pilot demo project is demonstrating indirect fired sCO_2 cycles to known available materials limits ($T>700°C$) in a fully integrated 10 MW_e electric generating pilot plant. Computer modeling of the pilot plant has been an important tool for design and for operations planning. The models will be validated by operational data, creating a powerful tool for future sCO_2 projects. 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 to begin in 2022.

ACKNOWLEDGMENTS

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DISCLAIMER

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