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# Dynamic Modeling for the 10 MWe $sCO_2$ Test Facility Program

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## Abstract

GTI is performing transient analysis using Flownex [1] to model the 10 MWe $sCO_2$ Brayton test facility being built on the Southwest Research Institute (SwRI) campus in San Antonio, Texas. Flownex is an object-oriented simulation environment that was developed in the late 1980s. It is ISO 9001:2008 and NQA1 compliant and has been validated in the nuclear industry. GTI has built models for both the simple Brayton cycle and recompression Brayton cycle (RCBC) configurations that will be tested in the facility. The steady state results of the model have been benchmarked against the Aspen Plus steady state model results for the design condition. This paper will review the implementation of components into Flownex and the control guidance from the model provided by the results of a startup simulation.

## Introduction

The STEP (Supercritical Transformation of Electrical Power) $sCO_2$ Facility is a 10 MWe net $sCO_2$ Brayton test facility being built on the SwRI campus in San Antonio, Texas. The effort to design, construct, and build this facility is funded by the DOE National Energy Test Laboratory (NETL). The objectives of this project and for this facility are to demonstrate the operability of the $sCO_2$ cycle, verify the performance of components (turbines, recuperators, and compressors, etc.), show the potential for producing a lower cost of electricity in relevant applications, and demonstrate the potential and pathway for a thermodynamic cycle efficiency greater than 50% in large scale (100 MWe and greater) power generation applications [2].

Steady state modeling has been performed for both the simple cycle and RCBC configuration of the facility [3]. The purpose of the steady state model was to provide the input for the technical specifications for each equipment unit in the facility to ensure successful target operation. Sizing and optimization of the components were based on the design point case of a 10 MWe RCBC cycle configuration with 715°C turbine inlet temperature. The RCBC sized components were then used in the off-design cases for both the RCBC and simple cycle configuration to determine the range of boundary conditions for each equipment unit.

Transient modeling is being performed for each configuration of the facility. The purpose of the transient model is to provide numerical results to aid in the operational analysis of the test facility. Transient operations, such as startup, shutdown, load level changes, etc. are being modeled. Control loop algorithms have also been incorporated to support definition of the distributed control system (DCS) requirements. Results of the transient model will help determine best control methodologies for the facility.

## Flownex Model Description

A simplified diagram of the simple cycle and RCBC configurations is shown in Figures 1a and 2a below. The corresponding Flownex models are shown in Figures 1b and 2b. In the Flownex model, the blue lines represent $CO_2$ flow, the orange lines represent heat transfer, the dashed lines represent data transfer links, and the solid black lines represent mechanical couplings.

For the RCBC configuration, $sCO_2$ is heated in the heater to desired conditions for that configuration. The $sCO_2$ passes through the turbine stop and control valve (TSV) and is then expanded through the turbine. Heat is recovered in the high temperature recuperator (HTR) and the low temperature recuperator (LTR) before the flow is split to the main compressor or the bypass compressor. The main compressor is driven by a Variable Frequency Drive (VFD) electric motor and the bypass compressor is driven directly by the turbine. Prior to entering the main compressor, the $sCO_2$ is cooled in the main cooler. Prior to entering the bypass compressor, the $sCO_2$ can flow through the bypass cooler or around the bypass cooler. Bypass loops including a heat exchanger are provided for both compressors to allow for them both to be started independently, as well as to provide anti-surge protection. The exit stream of the main compressor then flows through the LTR where it mixes with the discharge of the bypass compressor. The mixed stream flows through the HTR and then re-enters the heater. For the simple cycle configuration, $sCO_2$ follows mostly the same path as the RCBC configuration, except there is no bypass compressor loop. Downstream of the LTR, the entire $sCO_2$ flow enters the main cooler and main compressor.

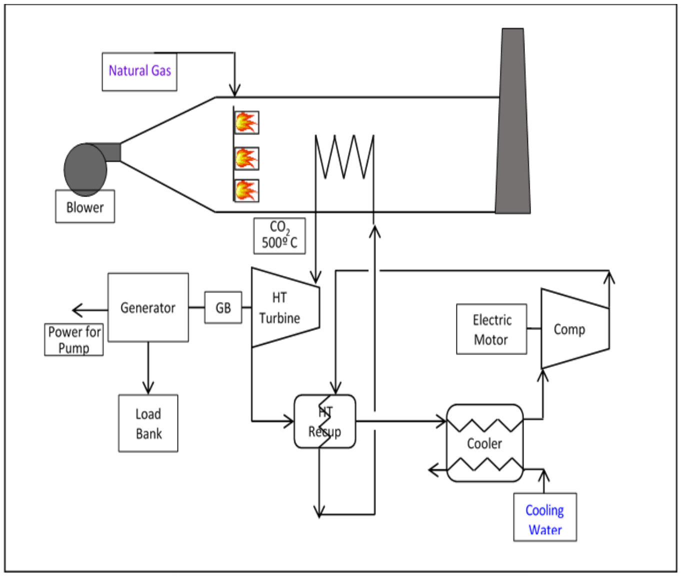

Figure 1a. Simplified Diagram of Simple Cycle Configuration [2]

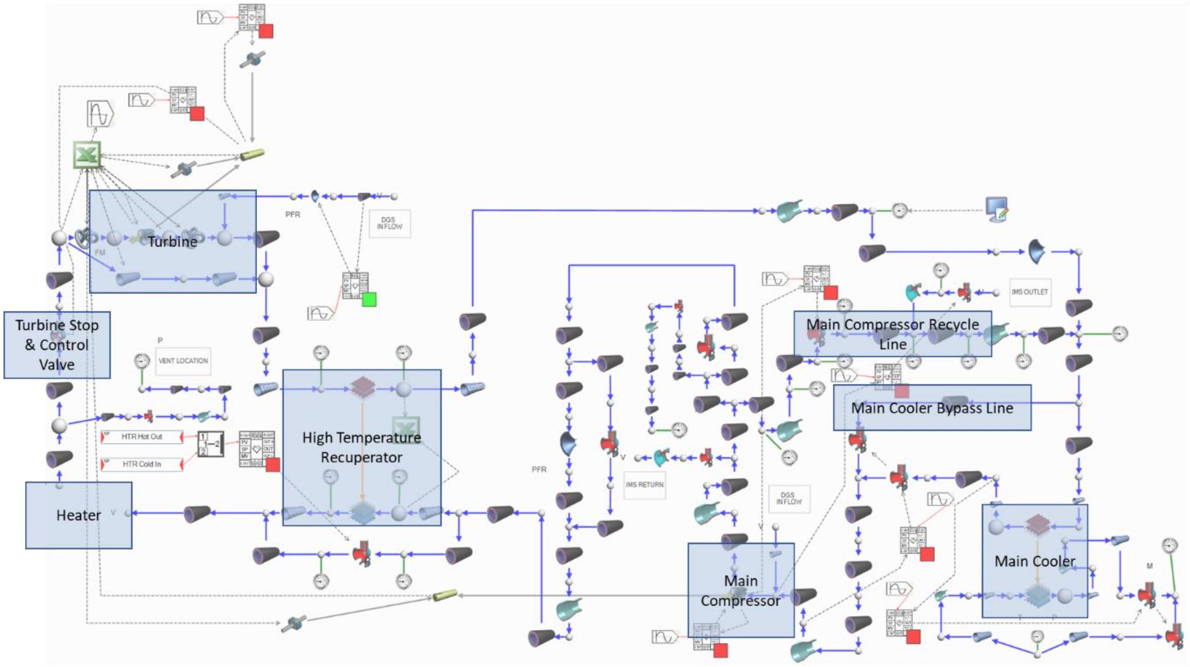

Figure 1b. Flownex Model of Simple Cycle Configuration

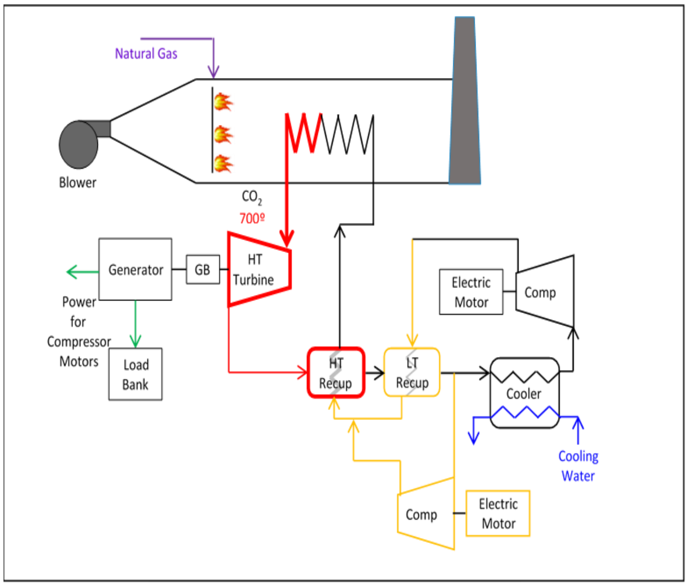

Figure 2a. Simplified Diagram of Recompression Brayton Cycle Configuration [2]

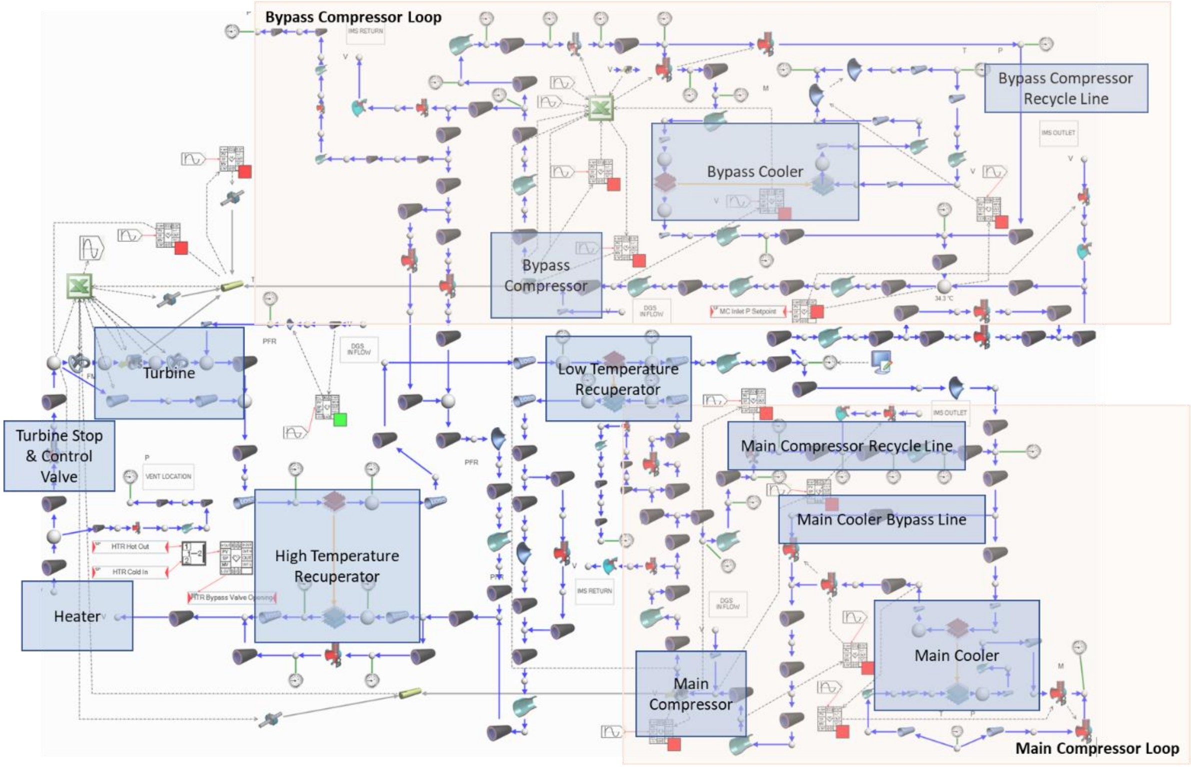

Figure 2b. Flownex Model of Recompression Brayton Cycle Configuration

The property method chosen is REFPROP, which is the best property method available for calculating $sCO_2$ properties at temperatures and pressures required for high efficiency Brayton cycles. The main area of concern in terms of accurately predicting properties is upstream of the main compressor, in which the operating conditions are extremely non-ideal. REFPROP is the most accurate in predicting properties in this region. Flownex creates a condensed table of $CO_2$ properties from REFPROP in order to have the model run closer to real time. The table is more refined around the critical point since small changes in temperature and pressure in this region result in large changes in the properties of $CO_2$.

Component geometries from vendor datasheets and operational constraints have been incorporated into the model. Individual component models have been benchmarked against vendor predicted performance data. Custom models have been built for the recuperators that incorporate adjusted heat correlations to align with the vendor predicted results. Results from the individual component models align well with vendor predicted performance. Results from modeling have been used to guide overall control logic and methodology. Validation of the model on a system level will be performed with the data from the facility during testing.

## Component Implementation

### Turbine

The STEP turbine is modeled in Flownex through a combination of Flownex elements linked to a spreadsheet that contains the turbine flow function, balance piston leakage, and inlet and exit pressure losses. Exit swirl is also accounted for in the exit pressure losses and is based on the exit swirl profile generator from GE.

Some secondary turbomachinery flows have been accounted for. Dry gas seal (DGS) flows that enter the main flow path have been modeled; however, oil flow in the bearings or instrument air used as a barrier gas in the dry gas seal packages have not been included.

## Recuperators

The high temperature recuperator, low temperature recuperator, main cooler, and bypass cooler are currently modeled using the plate heat exchanger element with customized heat transfer correlations. As detailed geometry of these recuperator cores, such as channel diameters, channel lengths, and # of channels, is proprietary to the vendor, these parameters were manipulated to better predict vendor performance. Average error deltas from vendor performance were less than 2% in predicted outlet temperatures and less than 0.2 bar for the pressure drops calculated.

## Heater

The heater has been modeled as a series of tubes with composite heat transfer elements to capture the heat transferred from the burner flue gas to the working $CO_2$ fluid. In this model, air is used to represent the combustion flue gas.

## Inventory Management System (IMS)

The inventory management system has been modeled, as shown in Figure 3 below. The IMS consists of a CO2 fill tank, vaporizer, vapor storage tanks, dry gas seal boost pump, and buffer tanks. The model starts downstream of the liquid $CO_2$ fill tank and vaporizer. $CO_2$ then goes to the vapor storage tanks and can either flow into the main and bypass loops or can flow through through the DGS lines.

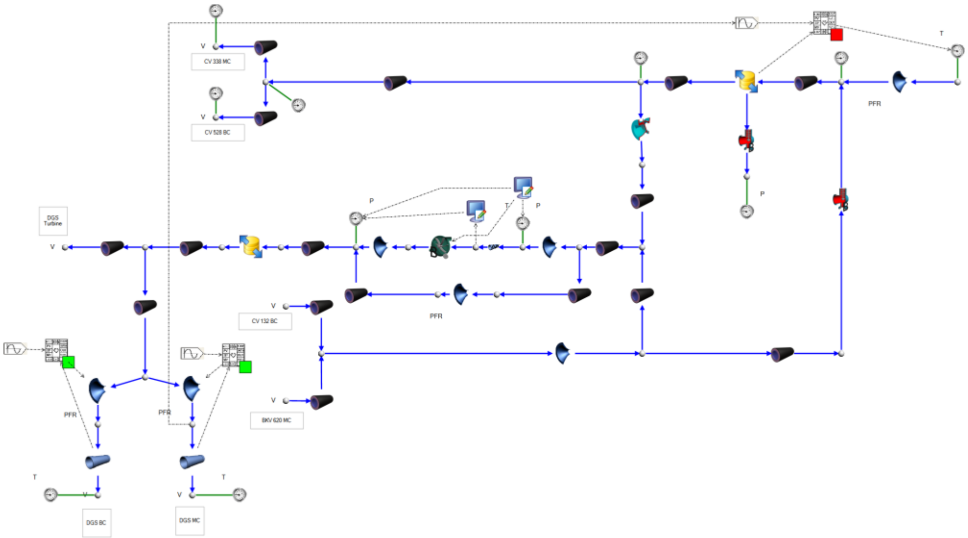

Figure 3. Inventory Management System

## PID Controllers

The controllers to be implemented in this facility for the main process loop have been incorporated into the model as PID (proportional, integral, derivative) controllers. 17 controllers have been incorporated: turbine speed control, turbine load bank control, turbine inlet temperature control, high side pressure control, compressor flow split control, main compressor inlet temperature control, bypass compressor inlet temperature control, bypass compressor inlet pressure control, main cooler outlet temperature control, bypass cooler outlet temperature control, low side pressure control, HTR bypass control, three DGS flow controls, and two compressor surge controllers. There will be inventory mass control for the facility, but this controller has yet to be implanted into the model.

### Compressors

The main and bypass compressors are modeled using compressor elements. Vendor maps have been incorporated using real gas properties. Initial Flownex format was in the form of corrected mass flow, but errors were found when compared to vendor performance with these as ideal gas assumptions lie within the conversion of the Flownex map format to usable thermodynamic parameters. Once real gas properties were used, no issues were found.

### Startup Results

Preliminary analysis using the model has been performed on the startup of both loop configurations. The startup duration for the simple and RCBC cycles was predicted to be about 7 and 10 hours, respectively. Start conditions for both configurations were assumed to be 50°C and 20 bar with zero power output. End conditions for the simple cycle case were 500°C and 217 bar turbine inlet conditions with 6.5 MWe net output power. End conditions for the RCBC case were 715°C and 250 bar turbine inlet conditions with 10 MWe net output power. The current rate limiting component is the heater, although further stress analysis is being performed by the heater vendor to determine if a faster thermal ramp rate is allowable, which could therefore reduce the startup duration.

Results from the transient model have provided guidance on startup control and methodology. Initial simulation results were run with $CO_2$ entering the system through the compressor and turbine dry gas seals with no $CO_2$ removal through the IMS until the discharge pressure of the compressors reached the desired steady state pressure, see Figure 4 for the initial startup pressure profile in blue. At that point, the IMS removed system mass to maintain pressure while the heater continued to heat up the system to design temperature. This simulation resulted in peak flow rates above equipment allowable design limits, as shown in blue in Figure 5. Total system mass flow through the loop was as high as 150 kg/s, almost 43% larger than the nominal design point flow rate. To reduce this peak flow rate, the simulation was modified to slowly increase the system pressure, as shown in orange in Figure 4, by using the IMS to remove system mass to control the compressor suction side pressures. This resulted in acceptable flow rates below equipment design limits, as shown in orange in Figure 5. From these results, the impact of IMS control on system pressure during startup can be seen.

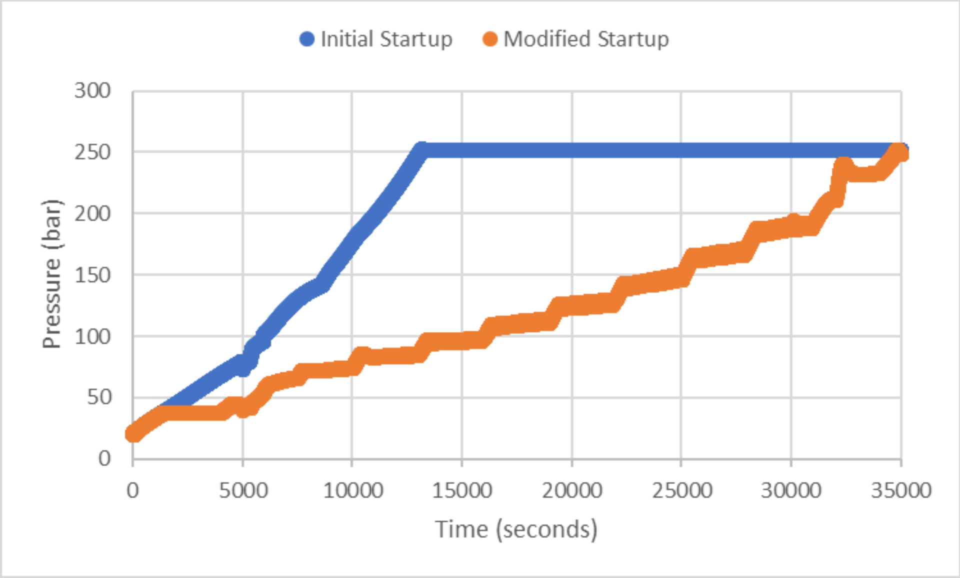

Figure 4. Initial and Modified Pressure Profiles for Startup

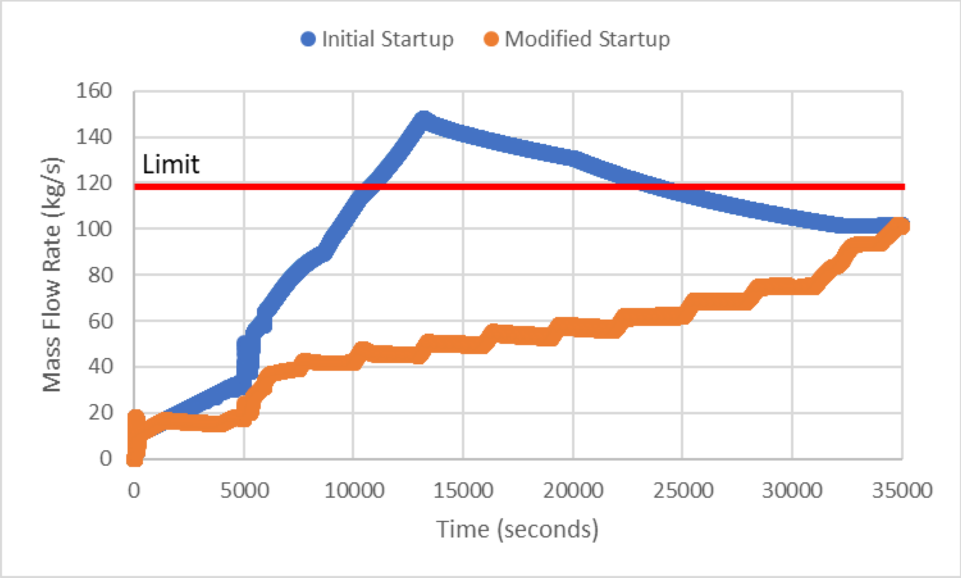

Figure 5. Peak Flow Rates for Two Pressure Profiles for Startup

One observation from the initial startup simulation showed that the $CO_2$ temperatures exiting the LTR low pressure side and entering the bypass compressor loop were low enough throughout the entire startup such that cooling was not required by the bypass cooler, as shown in blue in Figure 5. With the modified pressure ramp simulation, the reduction in system mass flow rate reduced the overall heat transfer rates in the HTR and LTR recuperators due to a lower Reynolds number and convection coefficient, which led to higher $CO_2$ temperatures exiting the LTR low pressure side and entering the bypass compressor loop, as shown in orange in Figure 6. These higher temperatures required cooling by the bypass cooler to prevent temperatures above specified limits. In this simulation, a little over 1 MWth of cooling was required. By varying the amounts of mass and heat additions and flowrates at various times in the simulation, the heat transfer rates in the recuperators could be optimized to result in lower temperatures entering the bypass loop to reduce the amount of cooling required by the bypass cooler, while also respecting system mass flow rate limits.

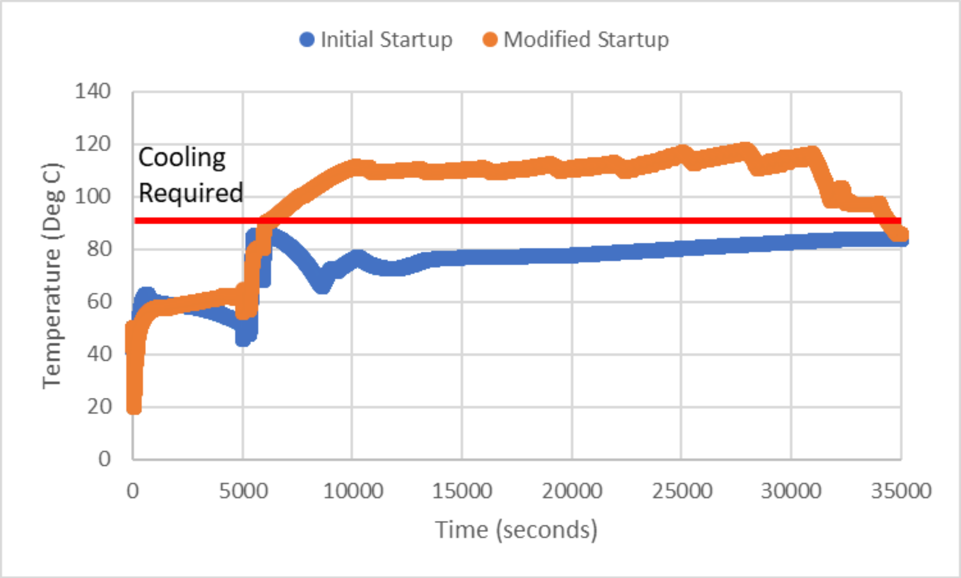

Figure 6. Temperature Profile of Bypass Cooler Inlet for Startup

## Shutdown Results

Shutdown simulations have been run for both Simple and RCBC configurations. The purpose of these simulations was to study the control methods and operational procedures needed to safely and stably shutdown the system while operating away from the extremes of the compressor maps and avoiding component mechanical limits.

Shown in Figure 7 is an RCBC normal shutdown in which the compressor shutdown sequence is varied to determine whether any component temperature limits are exceeded. As can be seen with the left-hand graph, the HTR low pressure side inlet temperature (red line) exceeds the 600°C limit. In this analysis, the compressor inlet guide vanes (IGV) move to their minimum position and the anti-surge valves (ASV) open prior to a reduction in heater firing to reduce the turbine inlet temperature. While flow through the turbine and HTR decrease, turbine power also decreases as the turbine reduces in speed, which causes the $CO_2$ flowing through the HTR to remain hotter as less heat is extracted from expansion through the turbine. In another analysis, heater firing was reduced prior to moving the IGVs and opening the ASVs, as seen in the right-hand graph. In this case, the HTR low pressure side inlet temperature limit was not exceeded.

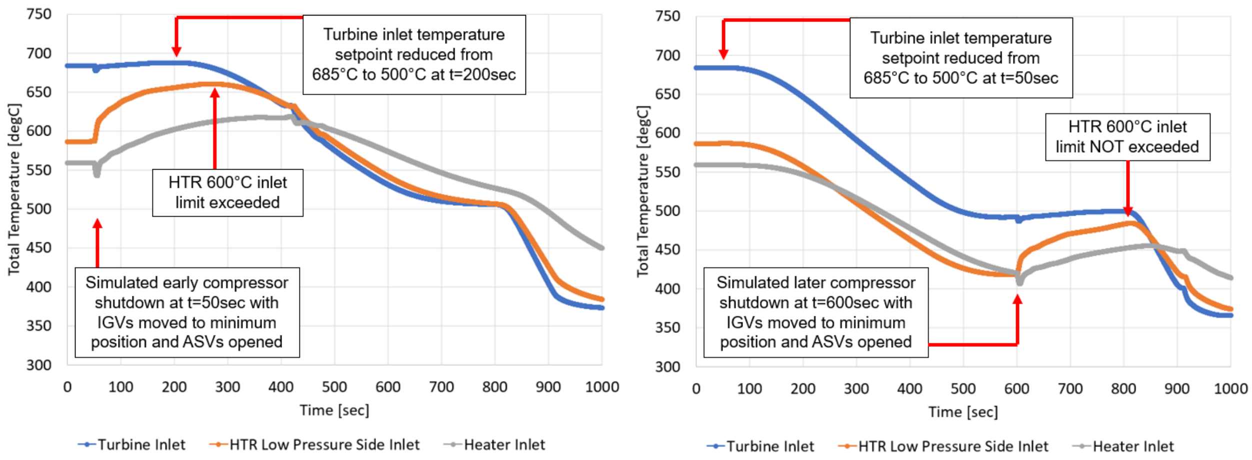

Figure 7. RCBC Normal Shutdown Varying the Compressor Shutdown Sequence

Other parameters observed during shutdown were generator load reduction and compressor map operation. Figure 8 below shows an RCBC normal shutdown in which the turbine inlet temperature is first decreased and then the TSV is closed. The degree to which the TSV closed affected the position on the compressor maps; thus, a sensitivity was run to determine the optimal closing position to maintain stable compressor operation. The IGVs were then moved to a lessor position to reduce flow and then the heater was shut down. All these actions reduced the generator load until the generator shut off. The TSV was then closed further to ramp the turbine speed towards zero, which then allowed the main compressor to be ramped down to zero speed for system shutdown.

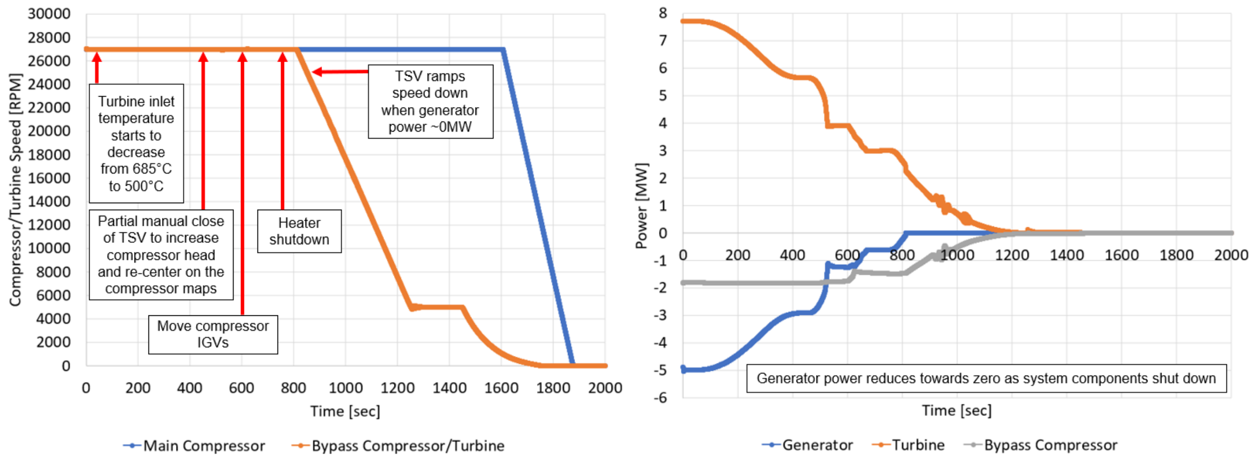

Figure 8. RCBC normal shutdown to study generator load reduction and compressor map operation

## Conclusion

A transient model has been built for both the simple cycle and RCBC configurations of the STEP facility. Updates to the model are made as more information is learned from the equipment manufacturers. Current equipment performance predictions have been benchmarked against component vendor predicted data. The transient model has and will be used to guide control methodologies, such as ensuring safe emergency shutdowns, defining how to start from cold or hot initial conditions, or ensuring stable operation as inventory is added and removed from the system. This model will be validated through testing of the STEP facility, at which point it will be the only validated transient model of a $sCO_2$ power plant (10 MWe scale). GTI will use this model to design and operate future power plants.

## References

[1] *Flownex® version 8.2.0.1735*

[2] Marion, J., Kutin, M., McClung, A., Mortzheim, J., Ames, R. (2019) “The STEP 10 MWe $sCO_2$ Pilot Plant Demonstration”, *Proc. ASME Turbo Expo GT2019-91509,* Phoenix, AZ.

[3] Huang, M., Tang, CJ., McClung, A. (2018) “Steady state and Transient Modeling for the 10 MWe SCO2 Test Facility Program”, *Proc. 6th International Symposium Supercritical CO2 Power Cycles*, Pittsburgh, PA.