The 8th International Supercritical CO_2 Power Cycles Symposium
February 27 – 29, 2024, San Antonio, Texas
Paper # 71

Simple Cycle Test Validation of the STEP Dynamic Simulation Model

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ABSTRACT

The STEP dynamic simulation model has been developed by GTI Energy utilizing Flownex Simulation Environment (Flownex SE) to model the 10 MWe sCO2 Brayton test facility in San Antonio, Texas. Flownex SE is an object-oriented simulation environment developed in the late 1980's that is ISO 9001:2008 and NQA1 compliant and has been verified in the nuclear industry. GTI Energy has generated models for both the Simple Brayton Cycle (Simple Cycle) and Recompression Brayton Cycle (RCBC) configurations that will be tested in the facility. The primary purpose of the model is to provide simulation results which would help in the operational analysis of the test program. Transient simulations that have been completed include startup, shutdown, load level changes, trips, etc. Control loop algorithms have been incorporated in the model to help determine adequate control methodologies for the test facility. Additionally, the dynamic model has been incorporated into a plant Simulator that operators can use to train on. With the completion of commissioning of all major components required for Simple Cycle operation, and the Simple Cycle test series successfully performed, this paper will discuss the verification process of the model components utilizing commissioning data, how the Simulator was developed, and the validation of the Simple Cycle model using test data.

INTRODUCTION

The STEP (Supercritical Transformation of Electrical Power) sCO2 Facility is a 10 MWe net sCO2 Brayton test facility on the Southwest Research Institute (SwRI) campus in San Antonio, Texas. The effort to design, construct, and build this facility has been led by GTI Energy and funded by the U.S. Department of Energy (DOE), National Energy Test Laboratory (NETL). The objectives of this project and for this facility are to demonstrate the operability of the sCO2 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 [1].

Steady state modeling has been performed for both the simple cycle and Recompression Brayton Cycle (RCBC) configuration of the facility [2]. The RCBC configuration utilizes two compressors in parallel to increase cycle efficiency. 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 targeted performance 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 so that the procured equipment would meet these specifications. Since testing will first be done in the simple cycle configuration, followed by reconfiguration to the RCBC configuration, the equipment needed to work for both configurations, with optimization for the design point case.

Transient modeling is being performed for each configuration of the facility using the Flownex program [3]. The purpose of the transient model (digital twin) is to provide numerical results to aid in the operational analysis of the test facility. Transient operations, such as startup, shutdown, load level changes from 10 MWe to ~5 MWe and back, etc. are modeled. Control loop algorithms have also been incorporated to support definition of the distributed control system (DCS) requirements. Results of the transient model help determine best control methodologies for the facility.

Figure 2a: STEP facility building (middle), cooling towers (right), heater and stack (middle), load banks (left)

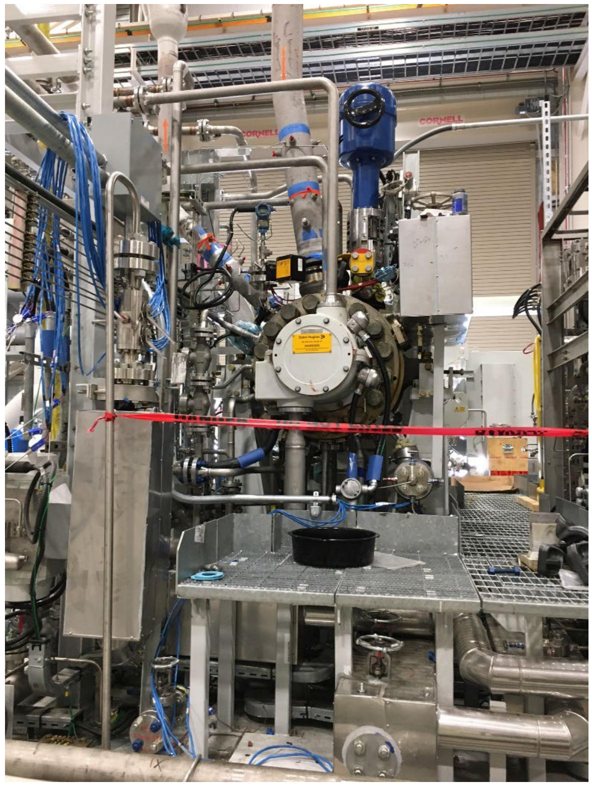

Figure 2b: Main compressor

Figure 2c: Turbine rotor

Flownex Model Description

A simplified diagram of the STEP Simple Brayton Cycle (Simple Cycle) configuration is shown in Figure 3a below. The corresponding Flownex model is shown in Figure 3b. In the Flownex model, the blue lines represent CO2 flow, the orange lines represent heat transfer, the dashed lines represent data transfer links, and the solid black lines represent mechanical couplings.

For the Simple Cycle configuration, sCO2 is heated in the heater to desired conditions for that experimental case. The sCO2 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) before the flow enters the main cooler and main compressor. The main compressor is driven by a Variable Frequency Drive (VFD) electric motor to control the speed of the compressor. Prior to entering the main compressor, the sCO2 is cooled in the main cooler. Bypass loops, which include the flow path from the compressors to the recycle valves and through the coolers, are provided to allow for the compressors to be started independently, as well as to provide anti-surge protection. The exit stream of the main compressor flows through the HTR and then re-enters the heater.

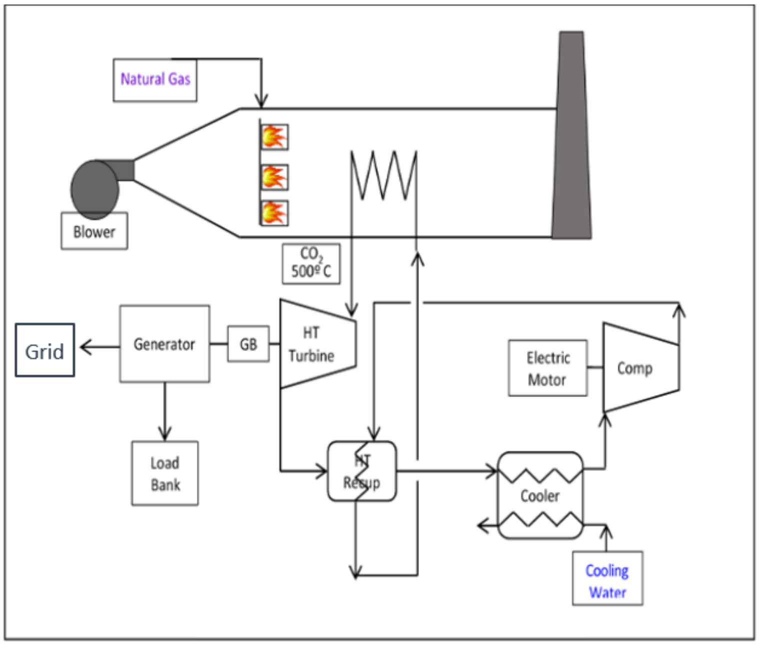

Figure 3a: Simplified Diagram of Simple Cycle Configuration [1]

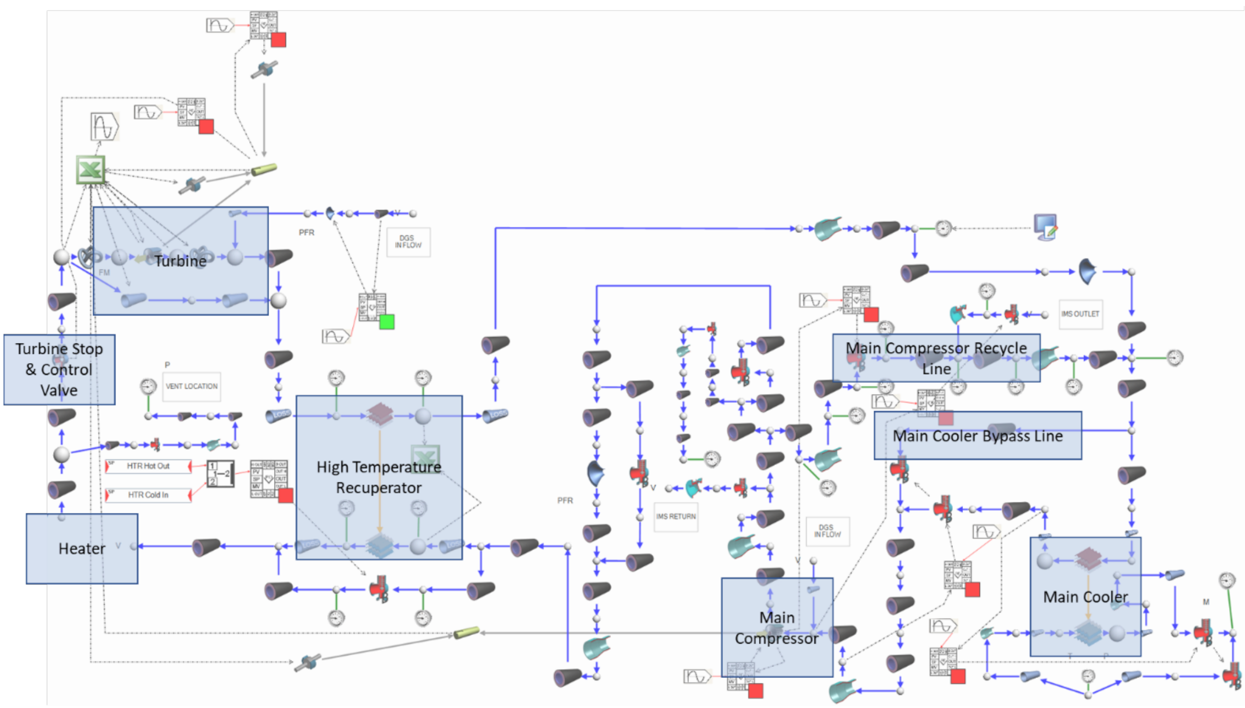

Figure 3b: Flownex Model of Simple Cycle Configuration

The property method chosen is REFPROP, which is the best property method available for calculating sCO2 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 CO2 properties from REFPROP in order to have the model run as fast as possible. If Flownex had to make a call to REFPROP at each iteration to determine

CO_2 properties, the software would run much slower. 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 in order to get the accuracy needed.

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.

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 and instrument air used as a barrier gas in the dry gas seal packages have not been included.

The high temperature recuperator and main 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 number 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.

The inventory management system (IMS) has been modeled. The IMS consists of a CO_2 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 the DGS lines.

The PID 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.

The main compressor is modelled using Flownex compressor elements. Vendor maps have been incorporated using real gas properties (isentropic head and efficiency versus volumetric flow). The only format initially in the Flownex software was in the form of corrected flow parameters that are based on ideal gas assumptions and are used in components such as engine turbochargers where those assumptions make sense. However, real gas property assumptions do not apply to sCO_2 compressors and large errors were found when comparing results to compressor vendor performance data. Once the Flownex software vendor added real gas property compressor maps into their software, good agreement was found between the Flownex simulations and the compressor vendor data.

RESULTS AND DISCUSSION

Test Validation Process Description

The general process for validating a model utilizing test data includes varying certain input parameters to "match" the available test data as close as possible. As mentioned previously, the current model contains components input parameters defined by vendor datasheets and vendor predicted performance data. Component geometries and properties are defined by the vendor datasheets and cannot be changed. Component input parameters associated with performance are the key parameters that will vary to match test data.

A simple example would be a fluid flow through a pipe measuring the pressure drop. The pipe geometry and dimensions – i.e. inner diameter and length – would be defined by the vendor datasheet; thus, are defined input parameters to the model that cannot be changed. Another input to the pipe would be a k-factor, or flow resistance factor. This would be required for a computational model to be able to calculate a pressure drop. Operational conditions would be the specific fluid, mass flow, temperature, and inlet pressure. Prior to performing the flow test, the model would predict the pressure drop along the pipe based on the inputs of the pipe. The actual performance of the pipe would be the outlet pressure or the pressure drop along the length of the pipe as measured during the test. Since the inner diameter and length are dimensions of the tested pipe that have been verified, to match the model calculated pressure drop with the measured pressure drop, the k-factor would be modified to match the test data. This would be the verification of the k-factor for the associated pipe.

Figure 4 shows a simple flow diagram of a typical test validation process for a computational model.

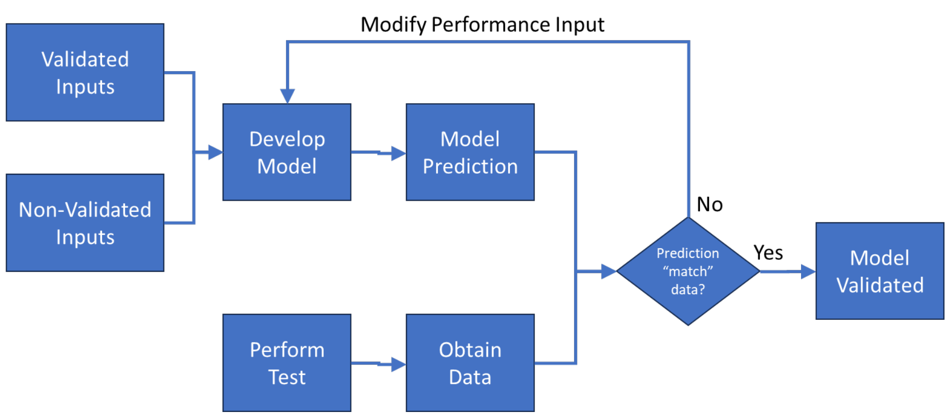

Figure 4: Simple Flow Diagram of Test Validation Process

Simple Cycle Component and System Commissioning Schedule and Planned Activities

Currently, the STEP Simple Cycle major component commissioning schedule is shown in Table 1. The schedule shown is correct as of the time of writing this paper, and the start and end dates are subject to change. Table 1 also indicates the input parameter(s) that will be modified to validate the component performance based on the test data obtained during commissioning.

Table 1: STEP Simple Cycle Component Commissioning Schedule and Performance Input Parameters

Component	Start Date	End Date	Performance Input Parameter
Main Compressor	Complete	Complete	Compressor Map
Turbine	11/20/2023	12/31/2023	Flow Function Pressure Losses
Heater	11/20/2023	12/31/2023	Heat Transfer Coefficients
System	1/1/2024	1/31/2024	Valves, Flow Resistance, etc

The project team is currently analyzing the Main Compressor commissioning data and updating the compressor maps. The first iteration of the updated compressor maps was incorporated into the steady-state model. However, convergence issues and unrealistic performance values were calculated. The updated compressor maps have not been incorporated into the dynamic model. The project team is currently modifying the compressor maps.

Once the validated compressor maps have been incorporated into the steady-state and dynamic models and verified to predict similar results to the commissioning data, the plan is to rerun all cases: startup, shutdown, load level changes, emergency trips. The priority will be to startup, which will compare the results to the previous runs to indicate the impact of the compressor map and modify the startup procedure as necessary. This process will repeat as each commissioning effort is completed and the validated performance input parameter is modified and verified.

<u>Applications of Dynamic Model: Emergency Trip Level 3 Simulation</u>

One purpose of the development of the dynamic model is to study and evaluate control methods and operational procedures for various scenarios. As mentioned above, standard procedures that have been simulated include nominal startup, nominal shutdown, load level changes, and emergency trips. This section will summarize the simulation and results of a Simple Cycle emergency level 3 trip to illustrate how the dynamic model is currently being utilized.

A level 3 emergency shutdown is a manually activated trip sequence via an operator by pressing the Emergency Shutdown (ESD) button. A level 3 trip is intended to completely and rapidly de-energize the plant. A level 3 trip sequence consists of isolating and stopping the turbine, opening of the compressor anti-surge valves, stop the main compressor, and venting the system of CO_2. Figure 5 shows the initial valve sequence.

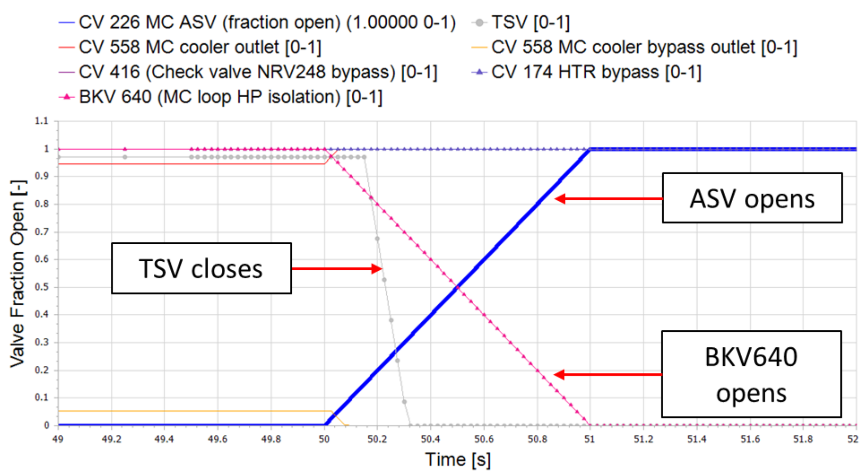

Figure 5: Emergency Level 3 Shutdown Initial Valve Sequence

Figure 6 illustrates the shutdown sequence and system result by showing turbine and compressor speed, system pressures and temperatures. 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 evaluated as test validated inputs are incorporated into the dynamic model.

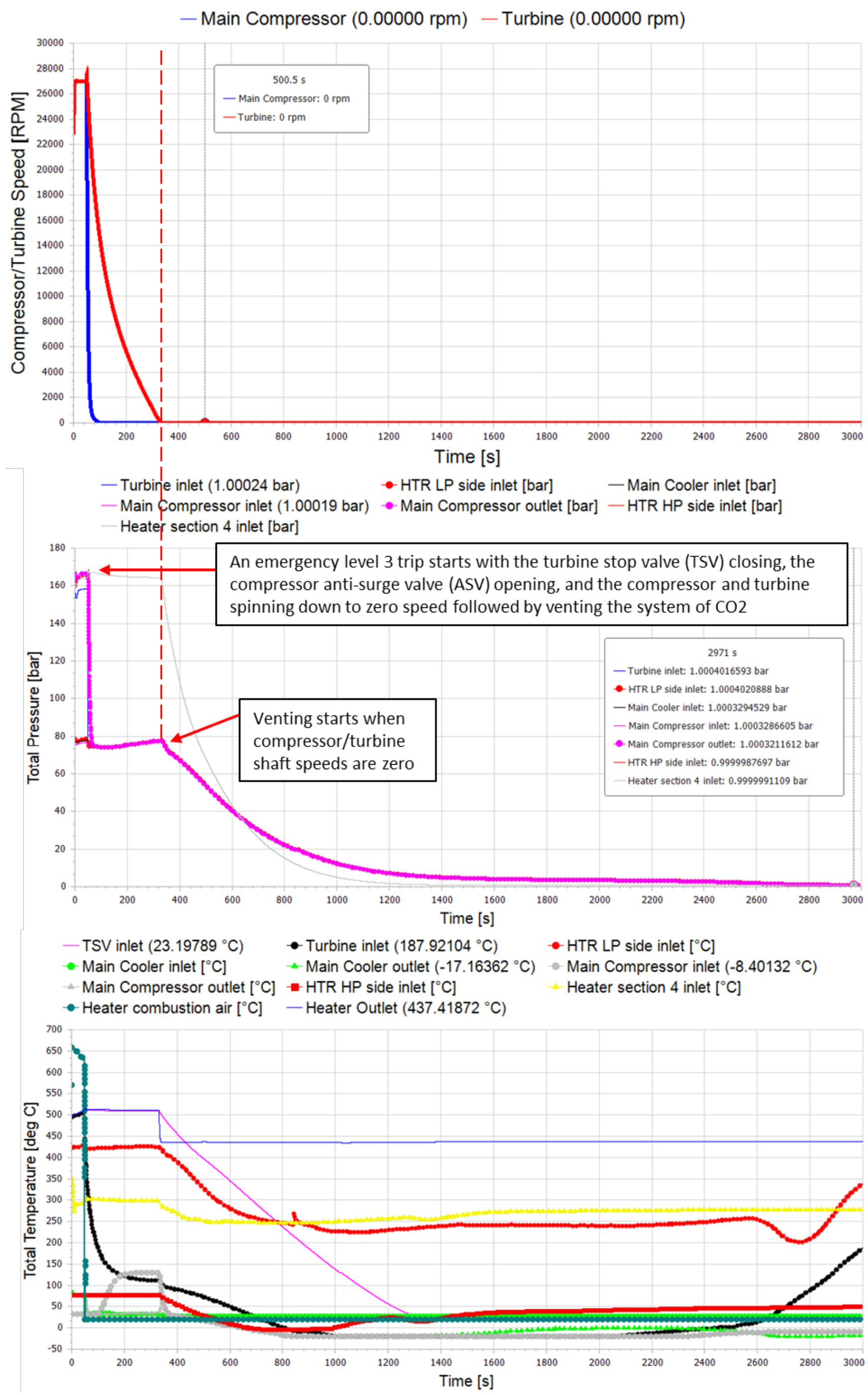

Figure 6: Dynamic Model Results for Emergency Level 3 Shutdown

Applications of Dynamic Model: Implementation of Digital Simulator

A virtual digital simulator (simulator) has been developed for the 10 MWe net sCO2 Brayton test facility. In 2022, the development of the simulator was completed, which included a startup simulator run that was evaluated, and modifications were made accordingly. Further work has been paused for the simulator, with plans to reinitiate the simulator during RCBC commissioning.

The purpose of the simulator is to predict and model system and equipment performance in an integrated power plant. This simulator will be used during operational planning, preparation of operating procedures, and operator training.

The dynamic model simulates the physics of the system hardware. The model ties into a GE virtual controller, which has the same I/O points and logic as planned for the test facility. Real time process data and control system data is passed between the model and the controller. A simulator executive code controls the process model and virtual controller to ensure the two run times are synched. The virtual controller ties to a human machine interface (HMI), which mimics the data control system of the facility. The HMI screens are the same as those planned for the test facility. Real time process data and control system data is passed between the virtual controller and the HMI. Operators will complete training using this simulator to gain familiarity with loop system dynamics, as well as to practice how to operate and control the system. By having the same GE controller and HMI screens, an operator training on the simulator will have the same experience practicing on the simulator as operating the real plant. Figure 7 illustrates the process flow of the simulator. [4]

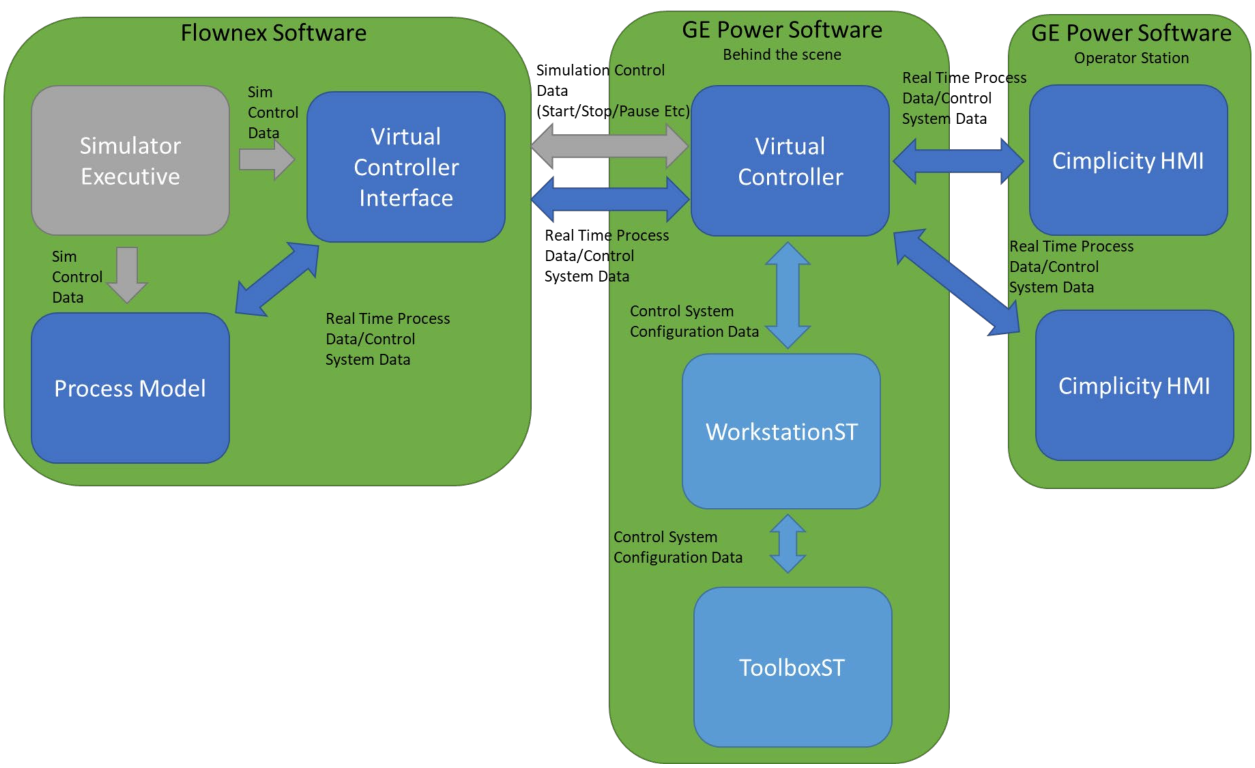

Figure 7: STEP Simulator Process Flow

Applications of Dynamic Model: UKAEA Shutdown/Startup Modeling

The $STEP_{USA}$ dynamic model was successfully used to predict transient shut down and start up events in the sCO2 cycle demonstration power plant. The start-up and shutdown simulated are intended to be indicative of the ability of a sCO2 energy conversion system to closely follow a pulsed input, three-hour period at power, then one hour off power generation pattern expected for the United Kingdom Atomic Energy Authority (UKAEA) power plant. The system shutdown takes less than five minutes paced by the inertia of the rotating equipment. The shutdown puts the system into a hot standby condition. During the one-hour hot standby hold system temperatures fall slowly as heat is conducted through insulation to the environment. Start up to power from hot standby takes less than 5 minutes paced by the rotating inertia of the turbine and compressors. The command to start up leads the net power up ramp by about three minutes. A short period of negative power is seen due power draw by the start-up of the motor driven compressor which leads the turbine/generator in beginning operation. The profile of the power command signal and resulting verses time for these events on Figure 8 shows how well the system responds. [5]

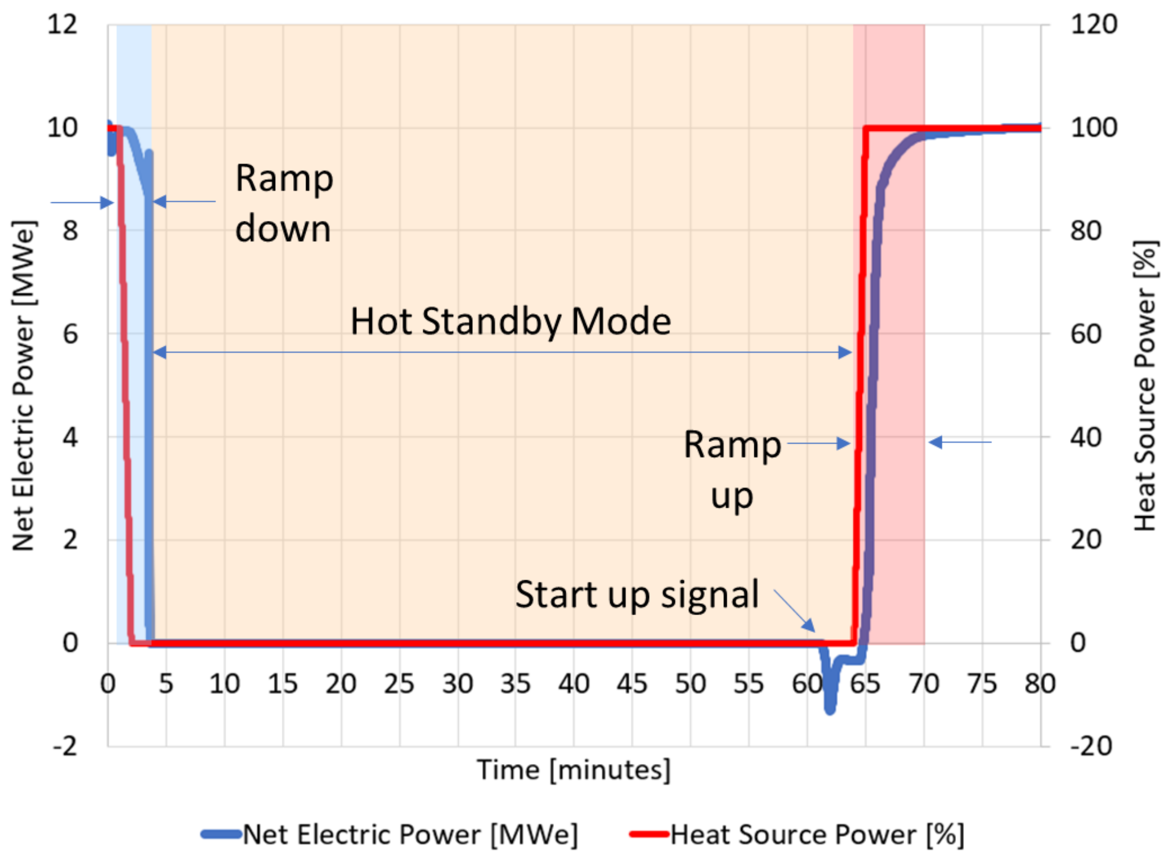

Figure 8: Rapid ramp rates of the $STEP_{USA}$ sCO2 power cycle effectively support fusion plant operation with one hour of standby time after every 3 hours at power.

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ACKNOWLEDGEMENTS

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