Supercritical CO_2 Power Cycles Symposium

Simple Cycle Test Validation of the STEP Dynamic Simulation Model

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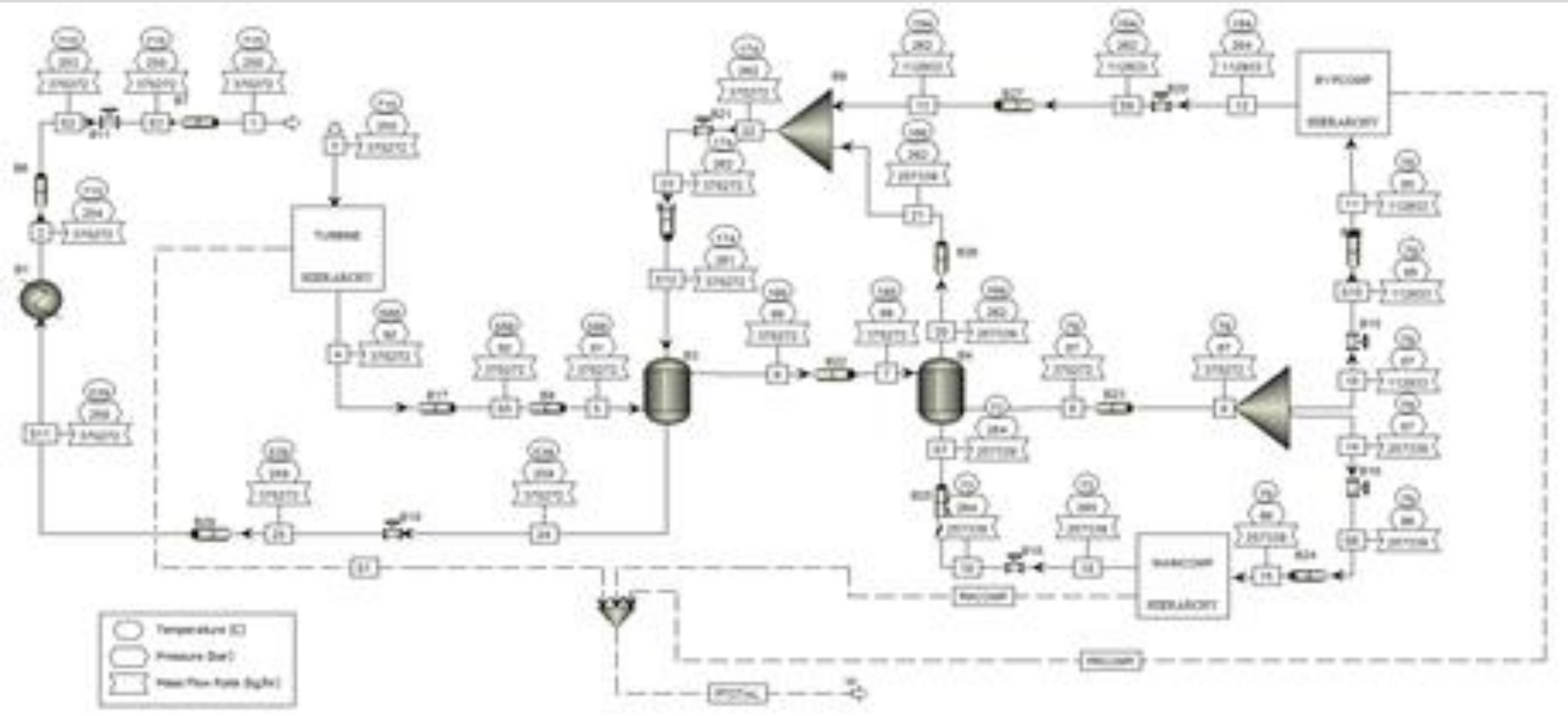
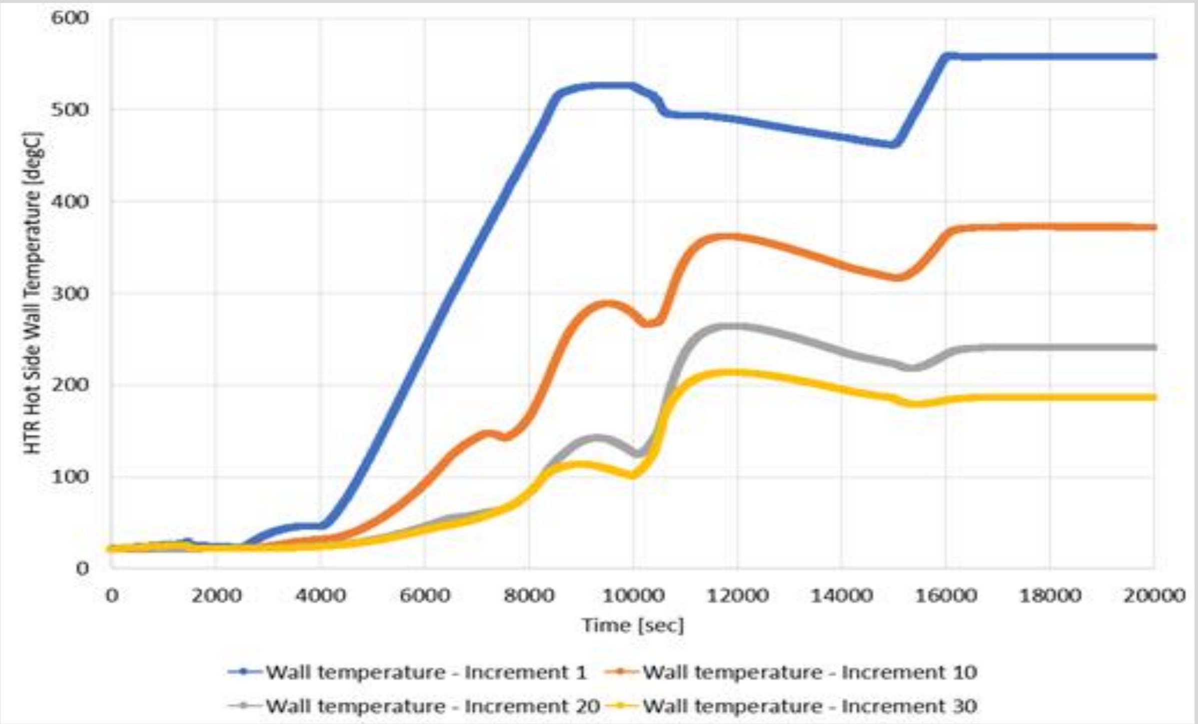
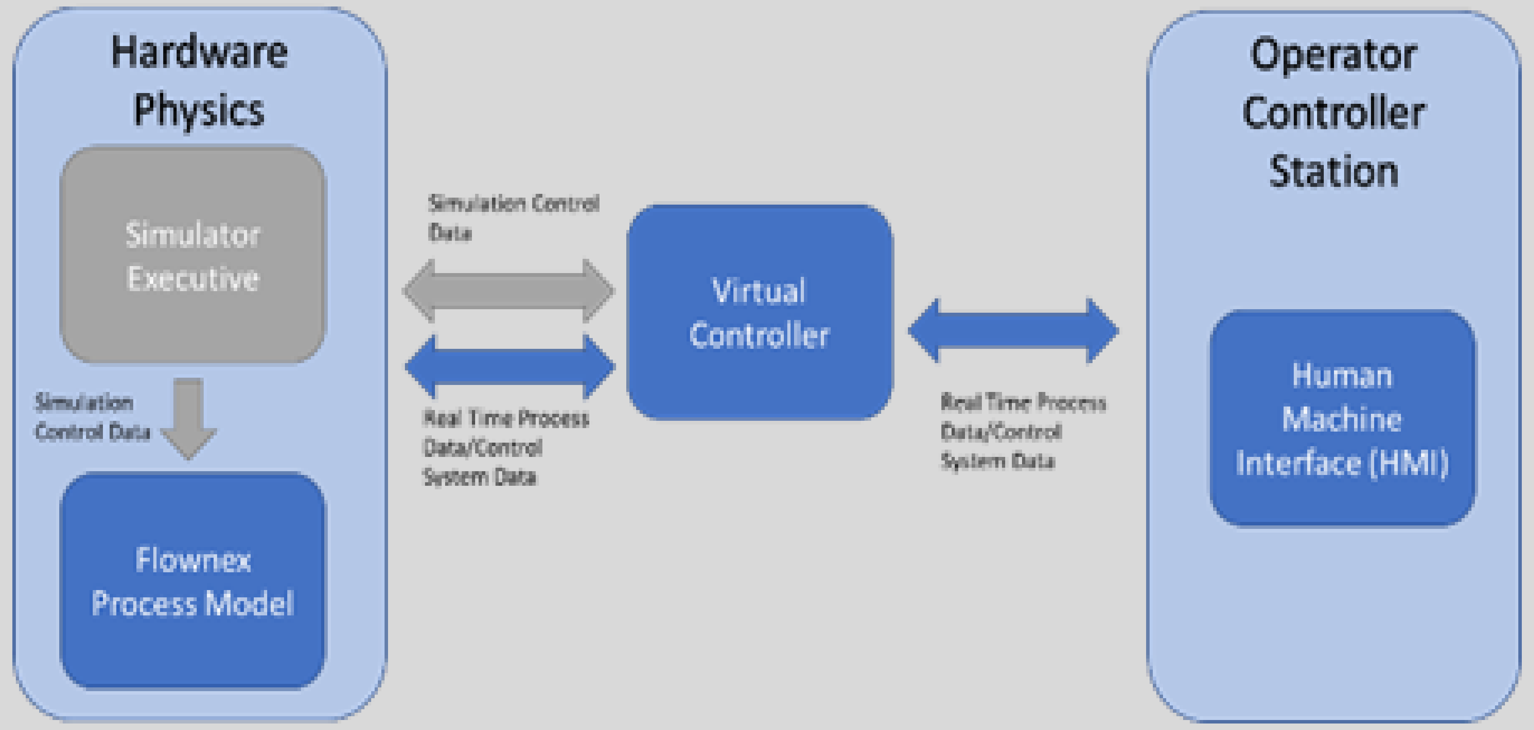
System Modeling An Increasingly Valuable Tool







Steady state modeling

- Development
  - Started Aspen Plus modeling ~12 years ago for system studies
  - Continuous improvement with realistic pressure loss & equipment performance
  - Cross verification w/other models
- Use
  - Cycle performance, pipe sizing, equipment specification
  - Evaluate other sCO2 cycles & applications

Dynamic modeling

- Development
  - Created Flownex model to support STEP
  - Calibrated against steady state model
- Use
  - Provide feedback on piping & equipment designs
  - Test controls narrative & methodology
  - Operations planning (startup, normal shutdown, and trips/shutdowns)

Facility simulator

- Development
  - Flownex model used for hardware physics
  - Ties into a virtual controller accesses real time data
  - Human machine interface mimics facility controls
- Use
  - Operator training – runs at real time
  - Operation planning

Models to be validated against STEP data for future use

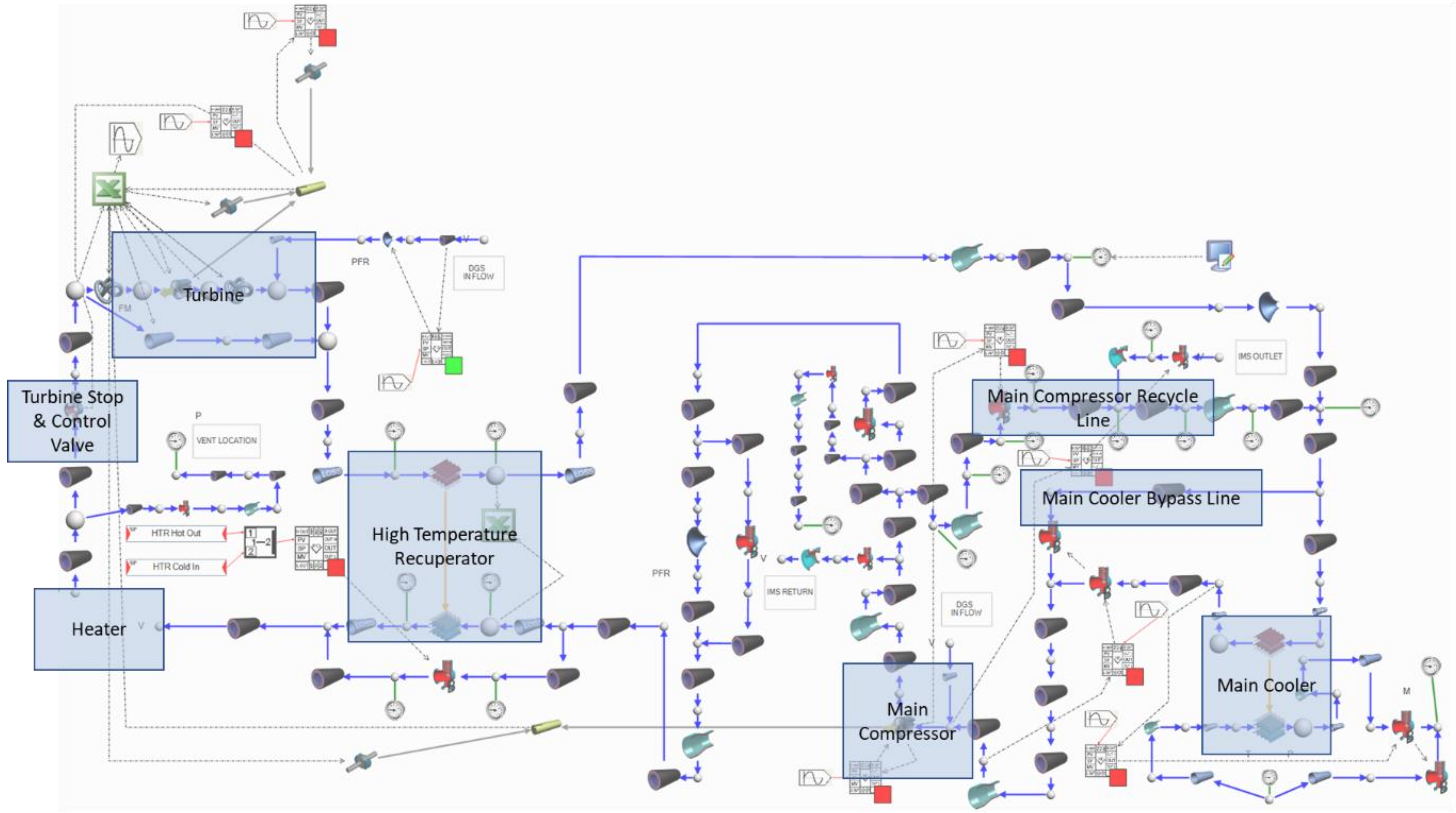
Dynamic Modeling Configurations and Purpose

- Steady state and transient analysis performed using Flownex software
- 2 models: one for Simple Cycle and one for RCBC configurations
- sCO2 properties are taken from NIST REFPROP
- Custom component models have been created and benchmarked against vendor predicted performance data
- Various transients have been analyzed, such as startup, shutdown, load level changes, and emergency trips
- Validation of the model will be performed as test data becomes available

Flownex SE Overview

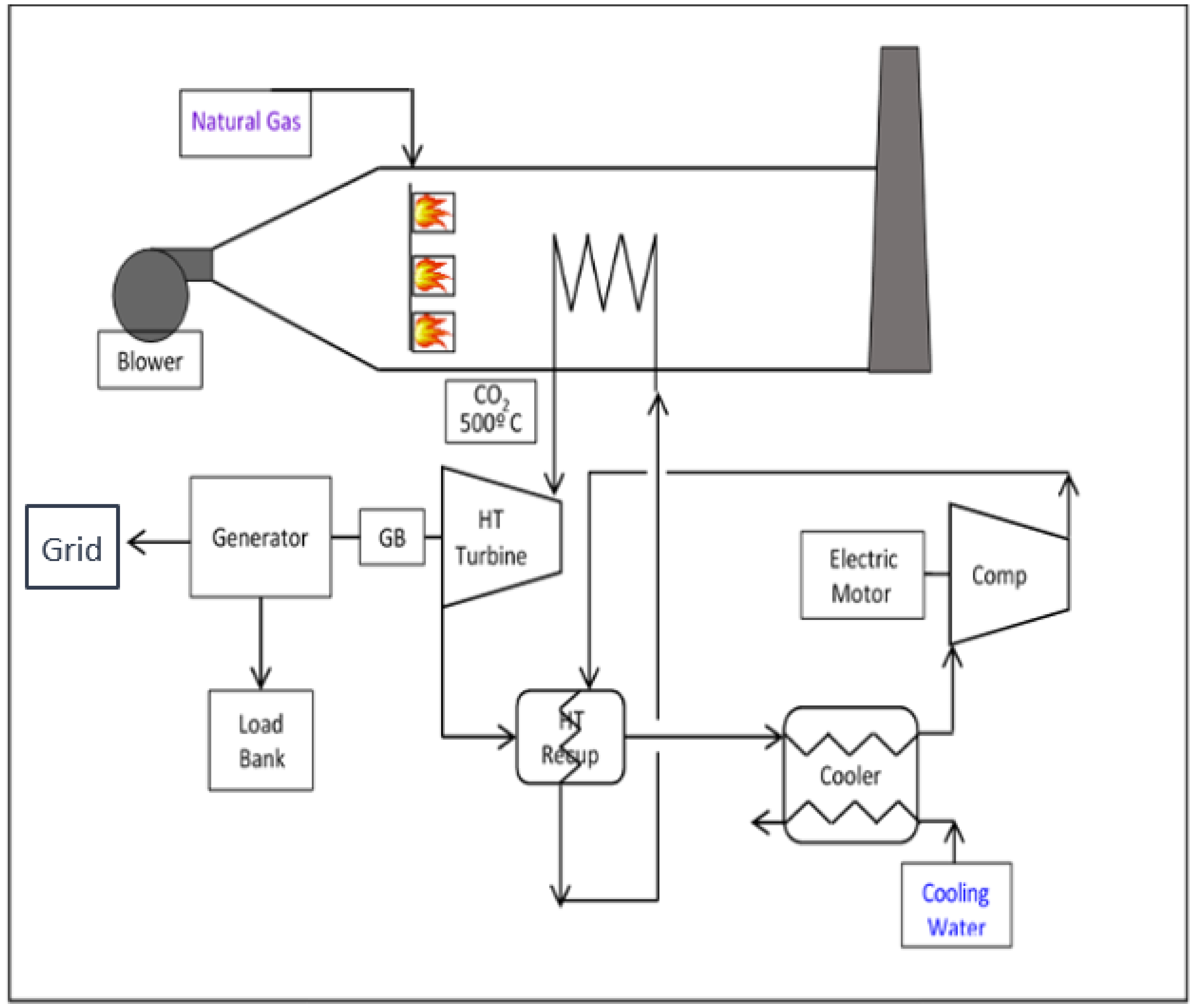
- Flownex Simulation Environment (SE) is an object-oriented simulation environment that was developed in the late 1980’s
  - ISO 9001:2015 and ASME NQA-1 compliant
- Allows for 1D integrated steady state and transient fluid flow and heat transfer system modeling to calculate pressure drop and heat transfer effects on the system
  - Typical uses include analysis, design and optimization
- Flownex SE has been applied to various industries:
  - Power, Gas Turbines, Aerospace, HVAC, Nuclear, etc

Reference: Flownex Simulation Environment



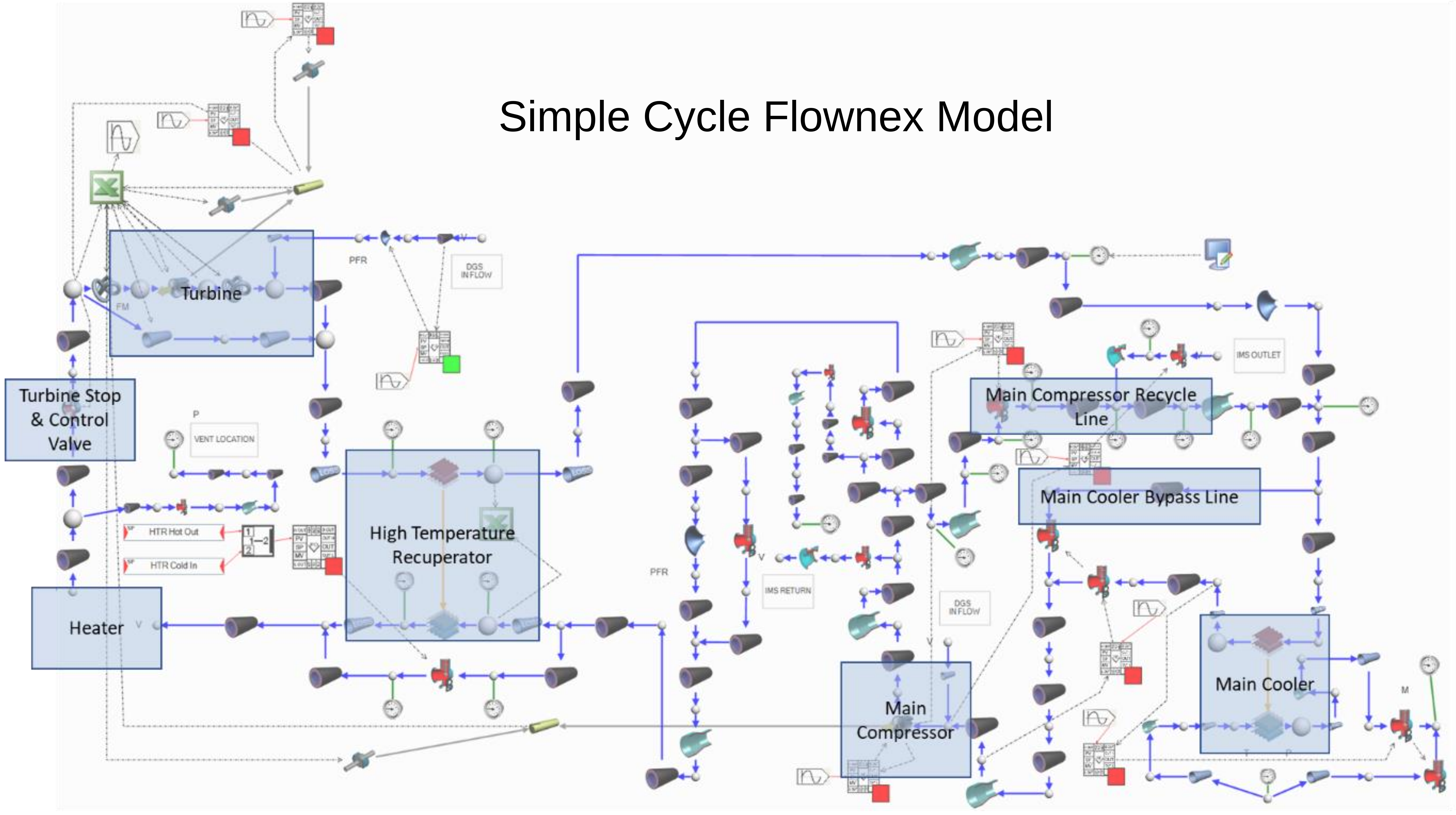
Flownex Model: Simple Cycle Configuration

Simple Cycle Overview



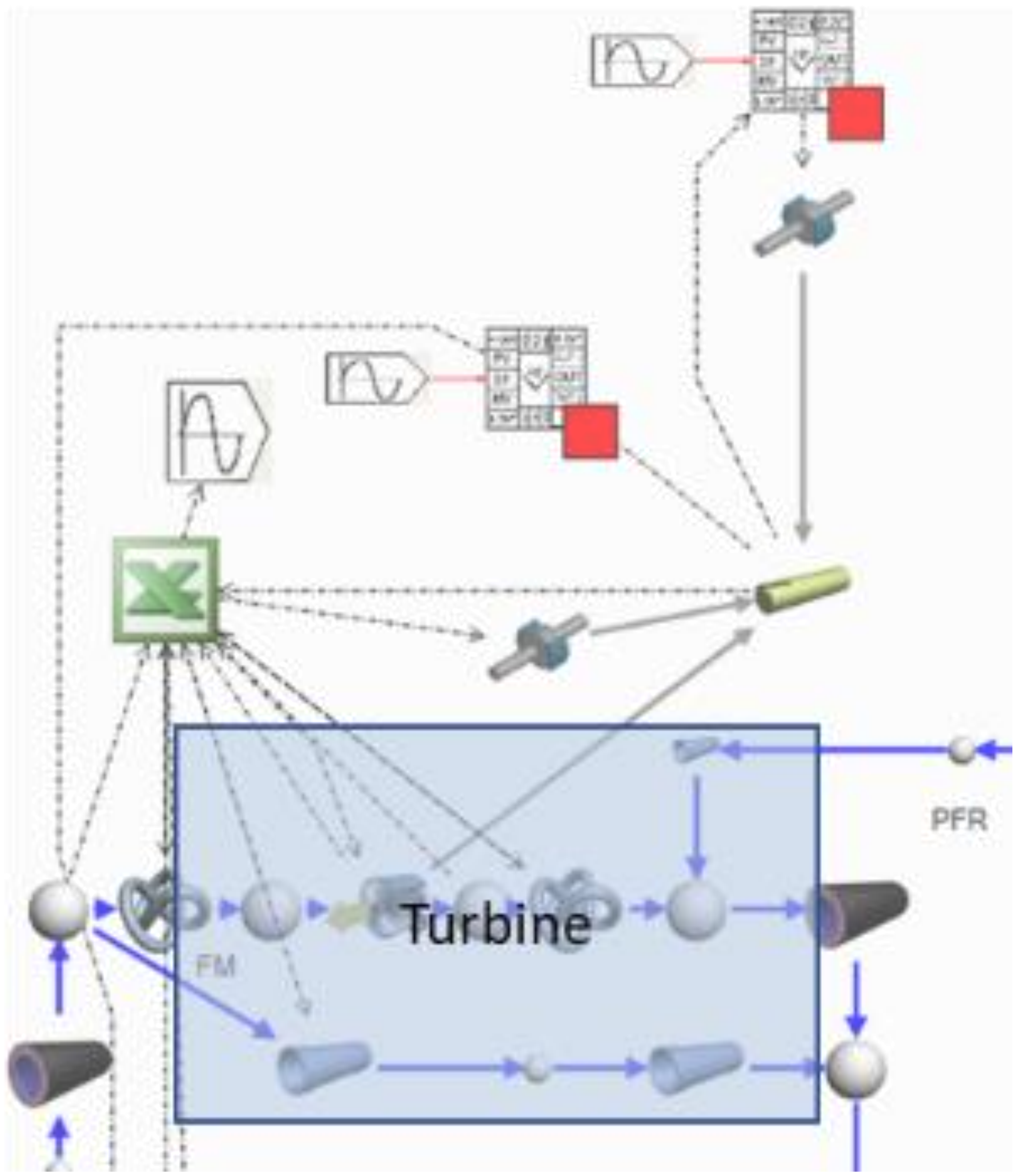
Simple Cycle Simplified Diagram

Simple Cycle Flownex Model



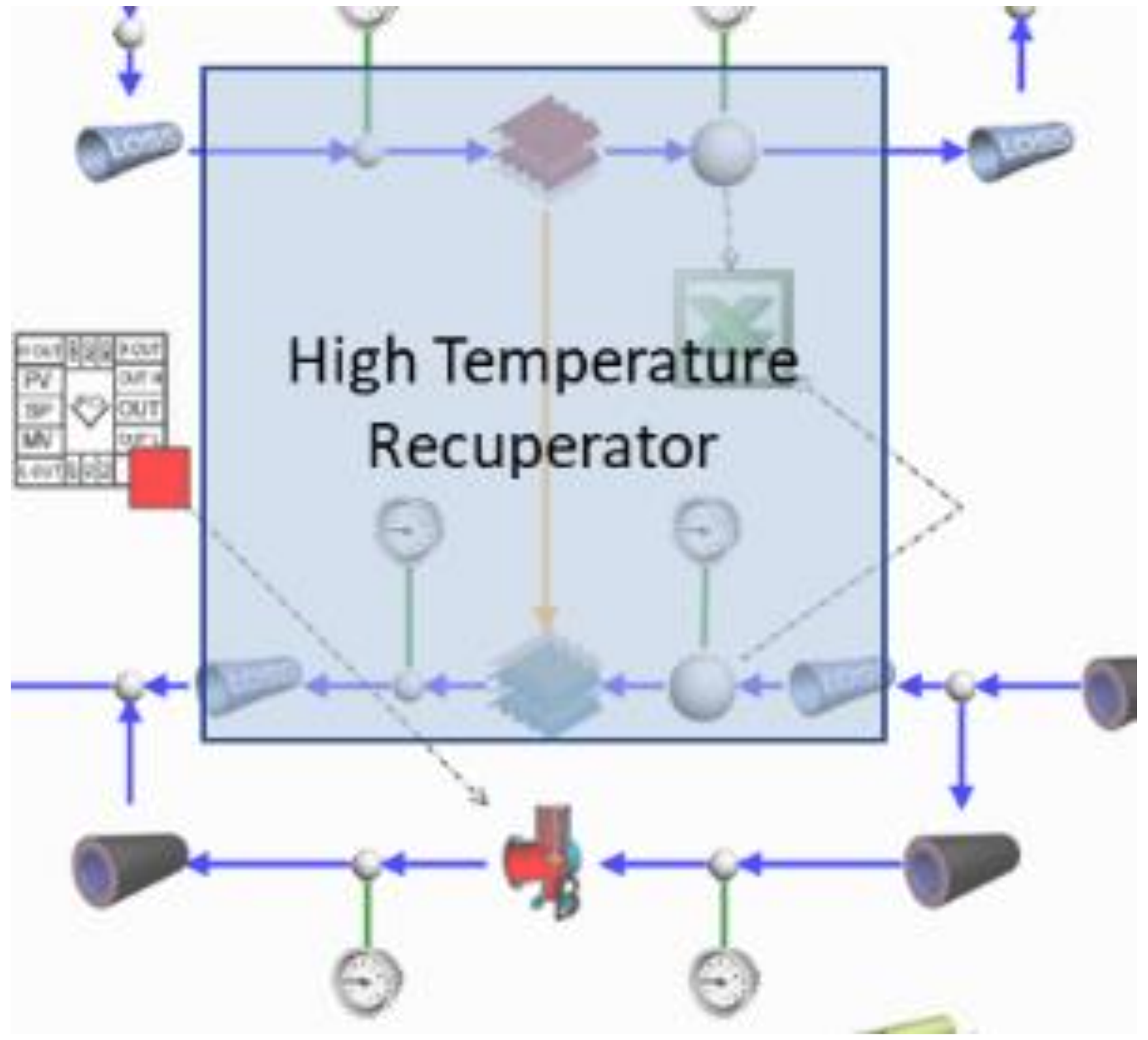
Component Implementation: Turbine

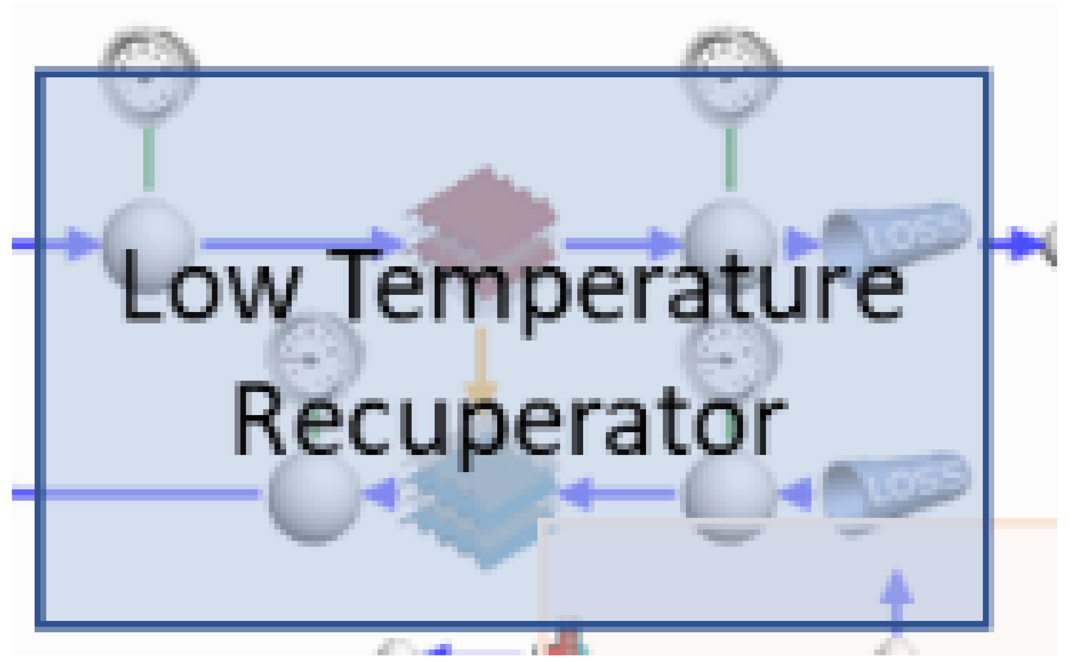
- STEP turbine is modeled through a combination of Flownex elements linked to a spreadsheet
- Spreadsheet houses calculations such as:
  - Turbine flow function
  - Balance piston leakage
  - Inlet and exit pressure losses
- Dry gas seal flows coming from the IMS are modeled

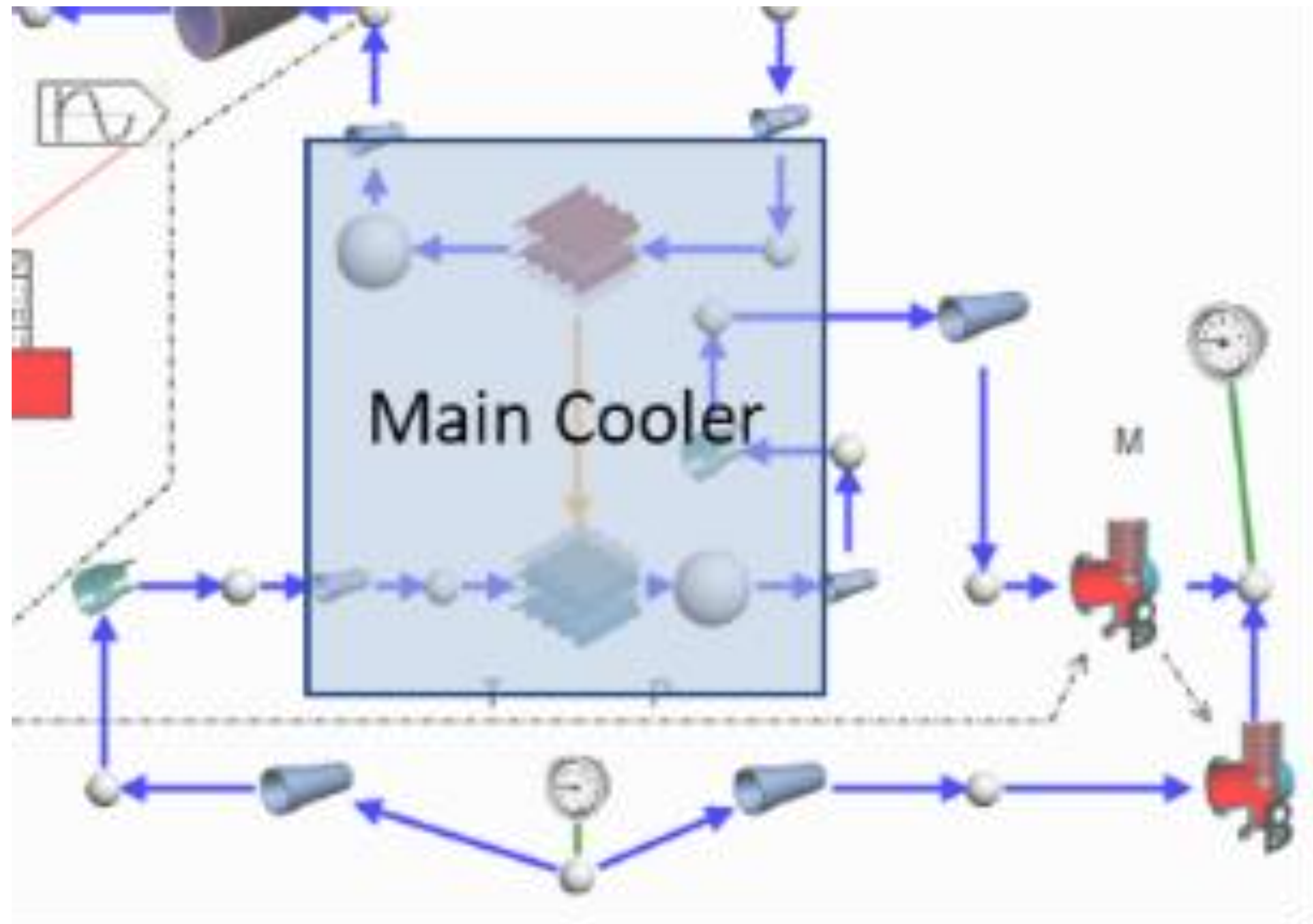


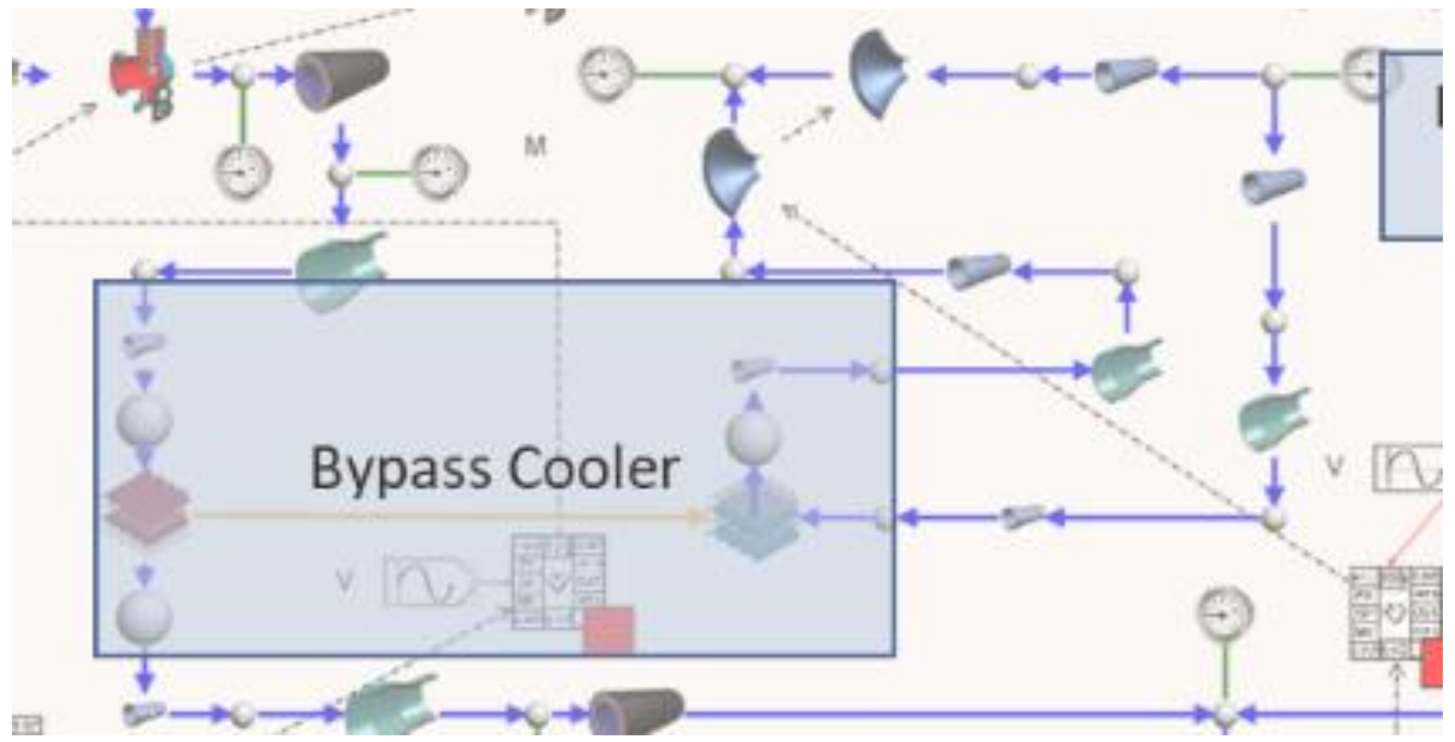
Component Implementation: Recuperators

- High temperature recuperator, low temperature recuperator, main and bypass coolers are modeled using plate heat exchanger elements with customized heat transfer correlations
- Error deltas were <2% in predicted outlet temperatures and <0.2 bar in calculated pressure drops



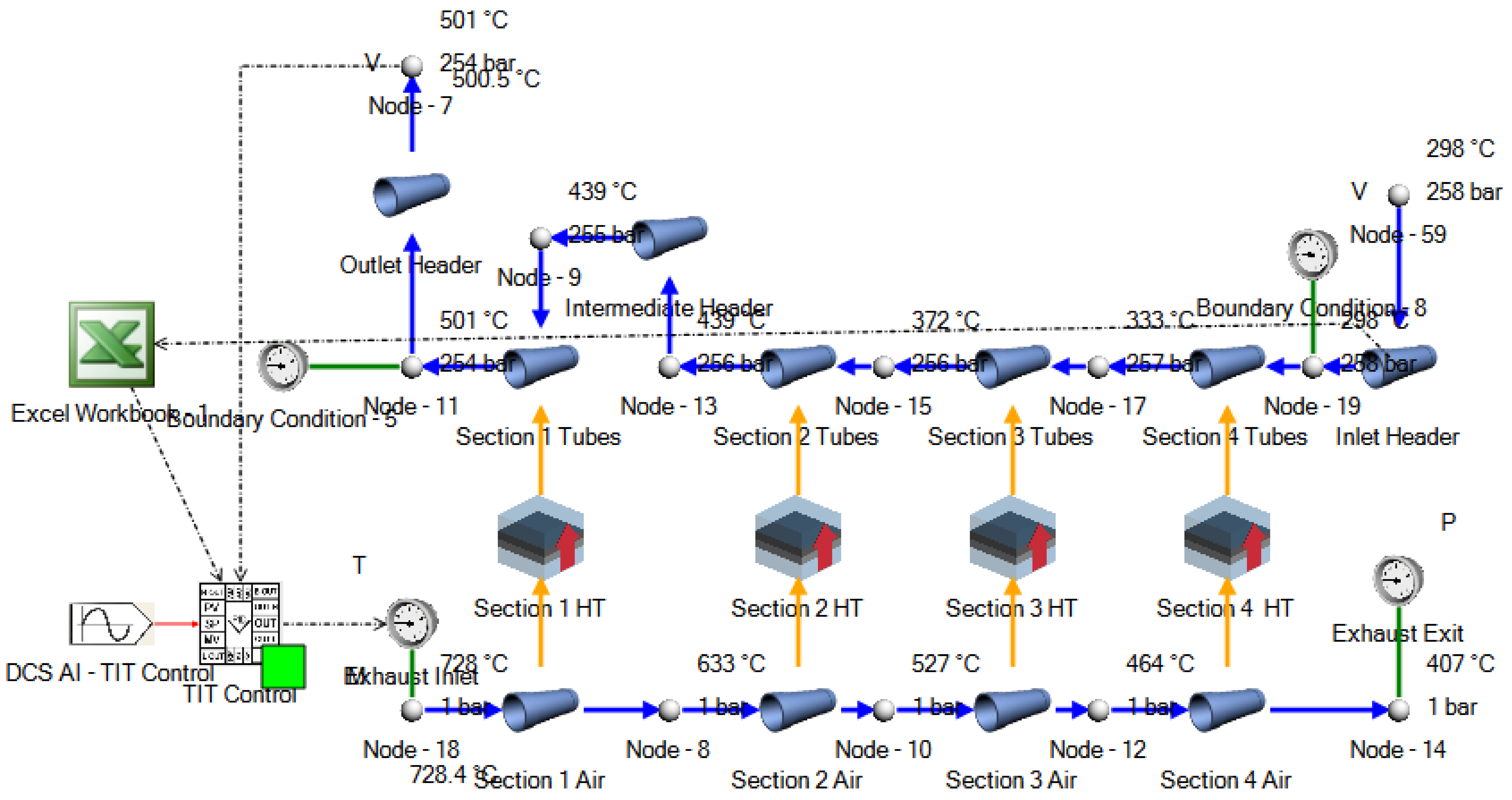






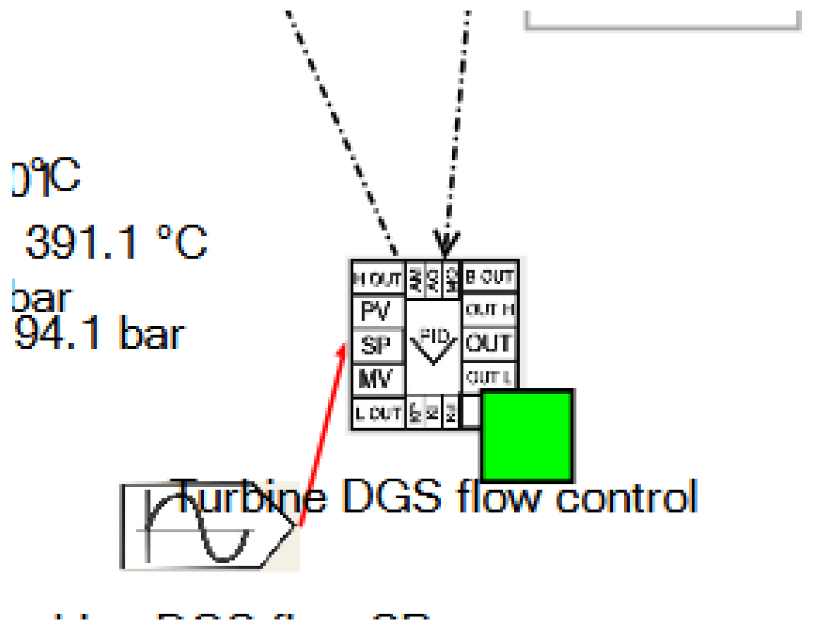
Component Implementation: Heater

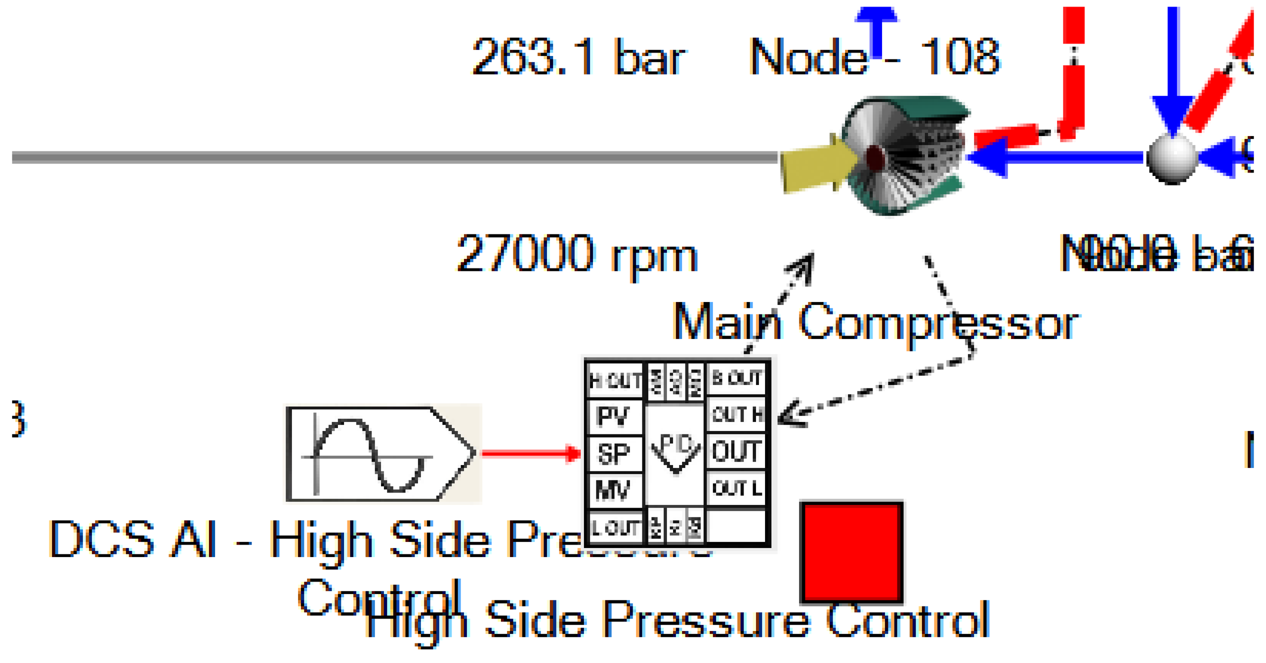
- Heater has been modeled as a series of tubes with composite heat transfer elements
- Modeling only the heat exchanger portion of the heater

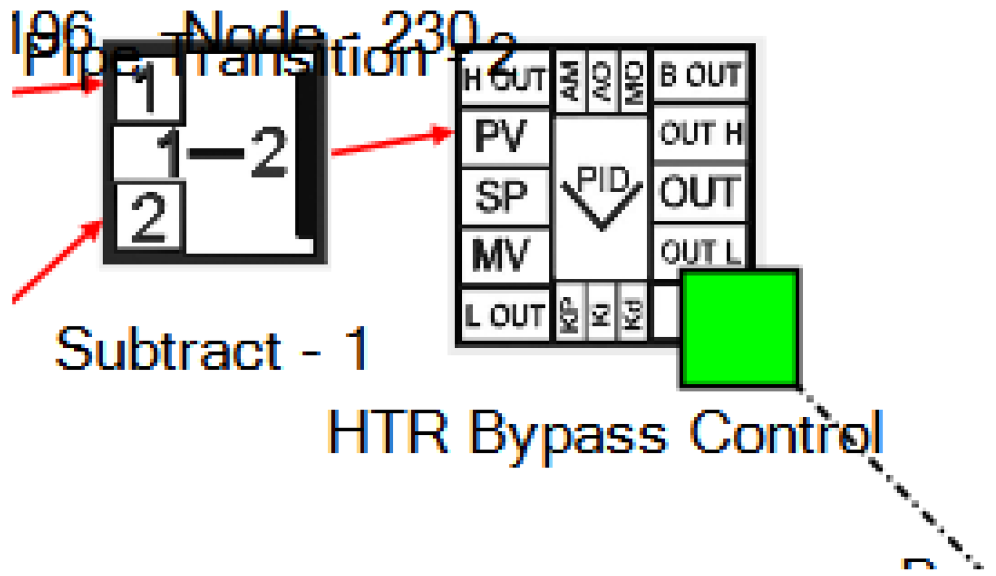


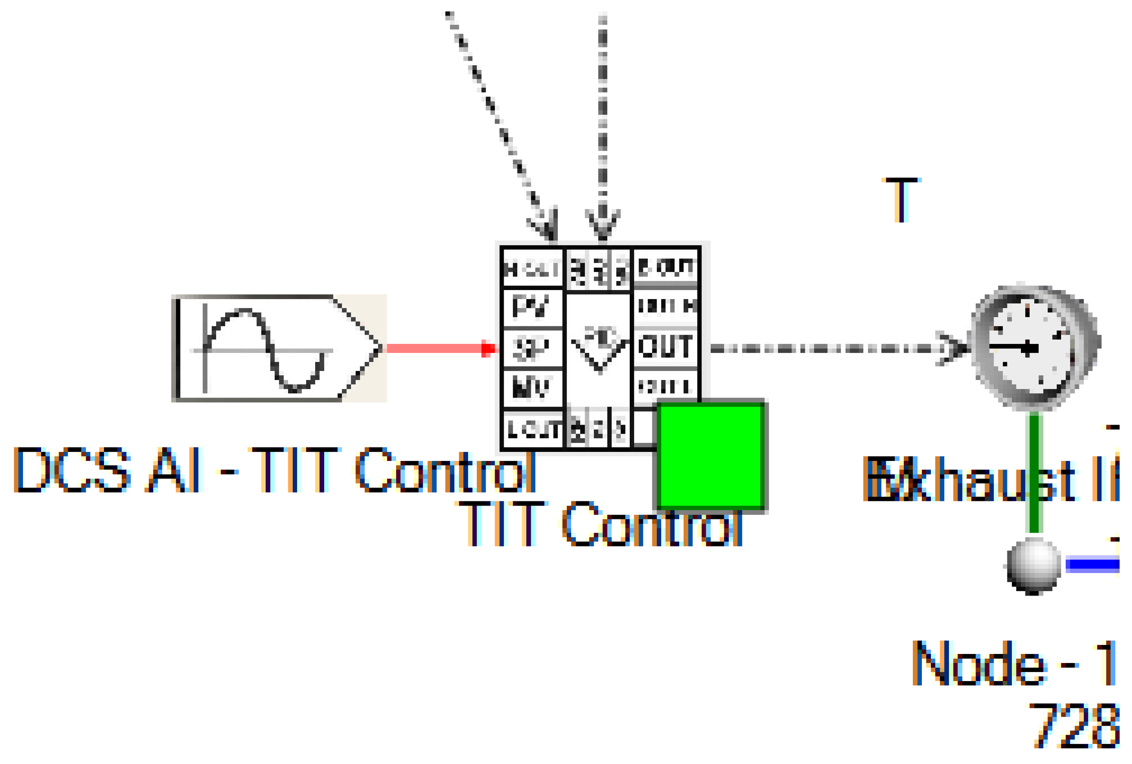
Component Implementation: PID Controllers & Compressors

- 17 total PID (proportional, integral, derivative) controllers in the model, used for automatic or manual control
  - Controlling speed, load, pressures, temperatures, mass flows
- Compressors modeled using Flownex compressor elements
  - Vendor compressor maps using real gas properties incorporated



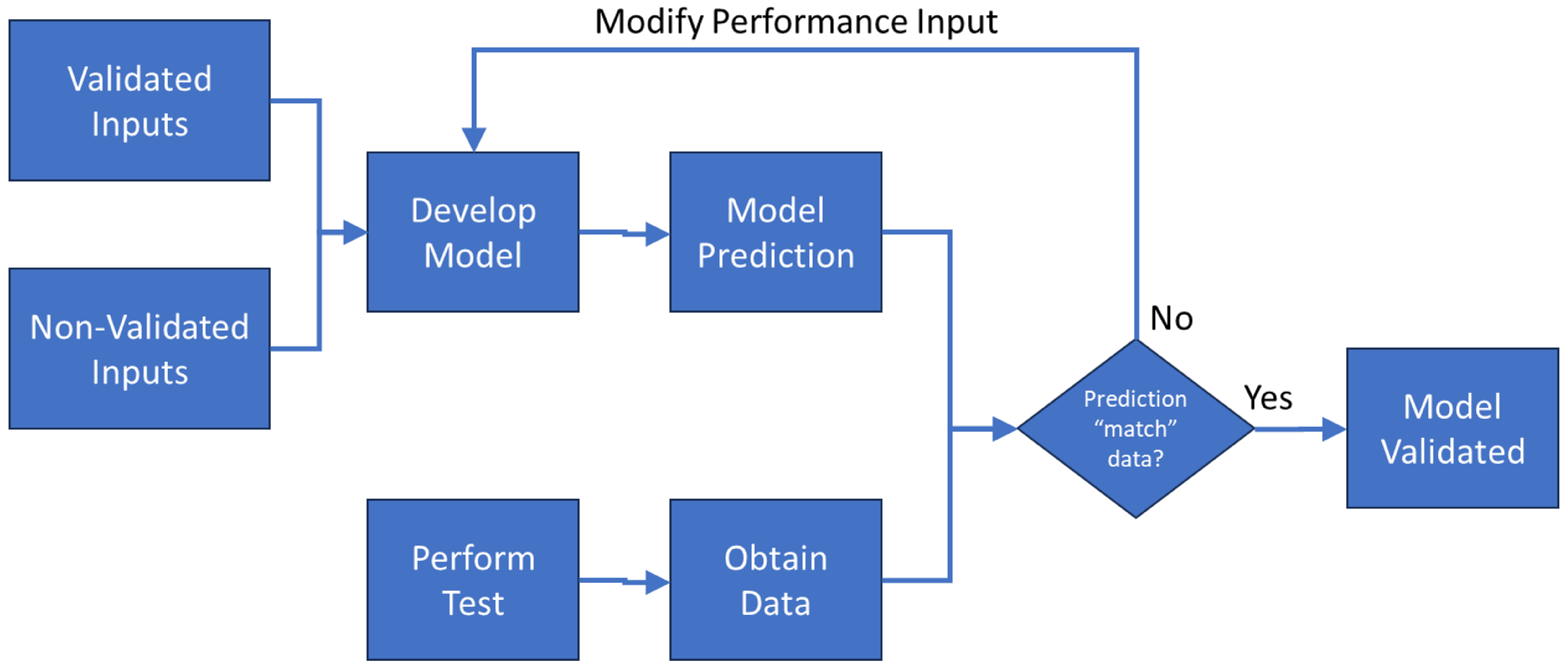


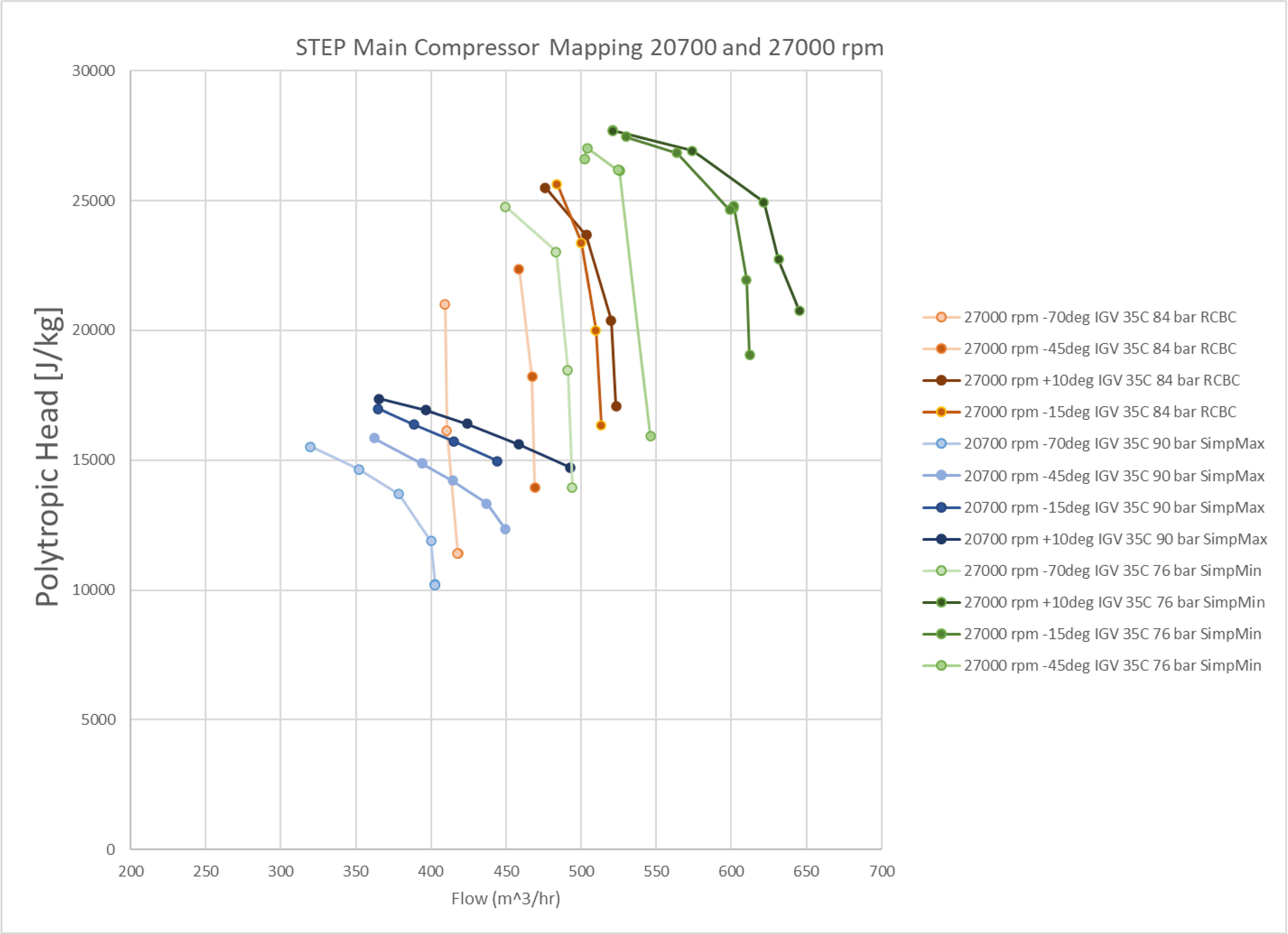




Test Validation Process

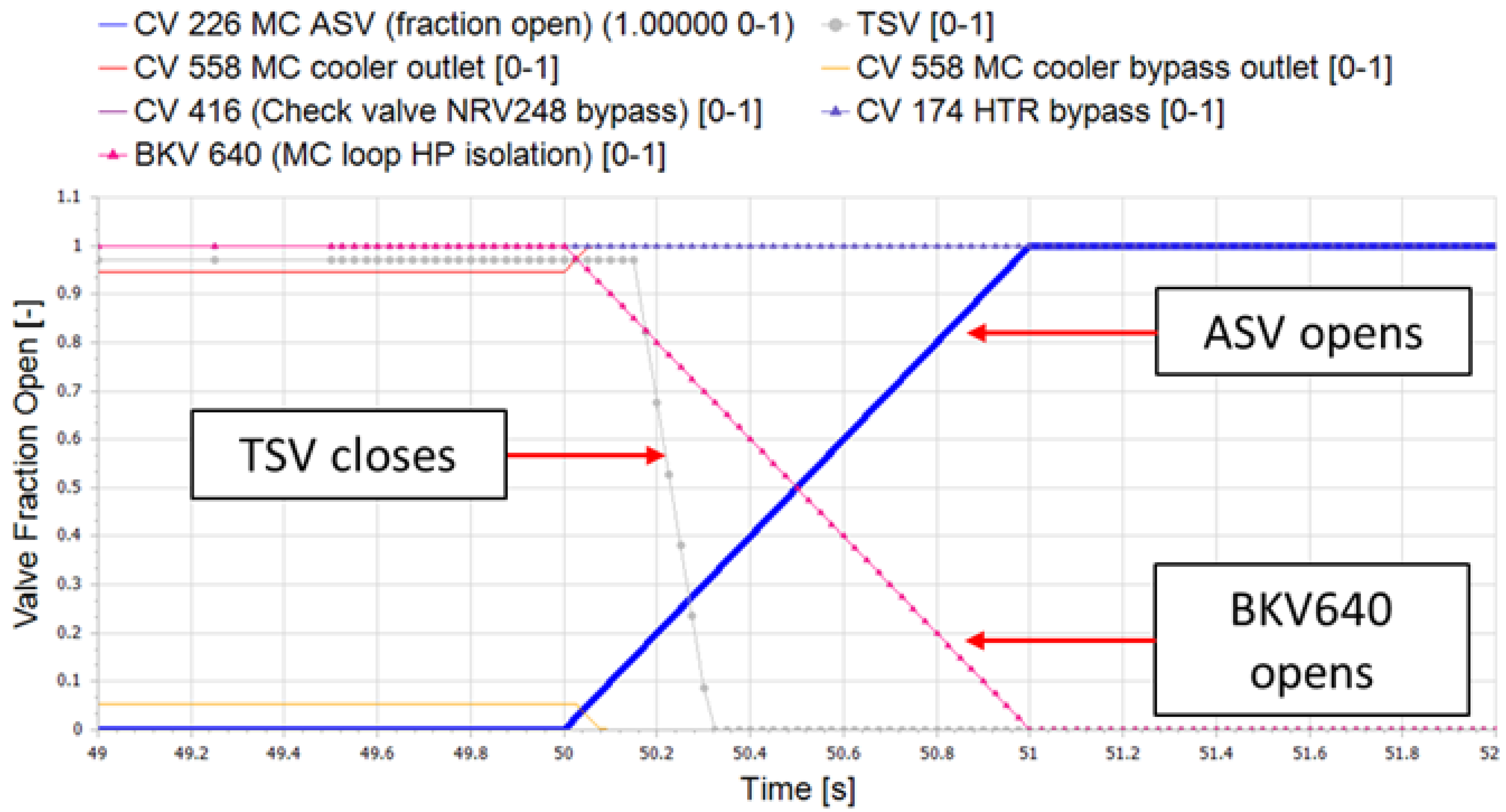
- Simple Cycle major component commissioning efforts have been completed
- Main Compressor maps have been updated and incorporated into the steady-state and dynamic models





Application of Dynamic Model: Emergency Trip L3

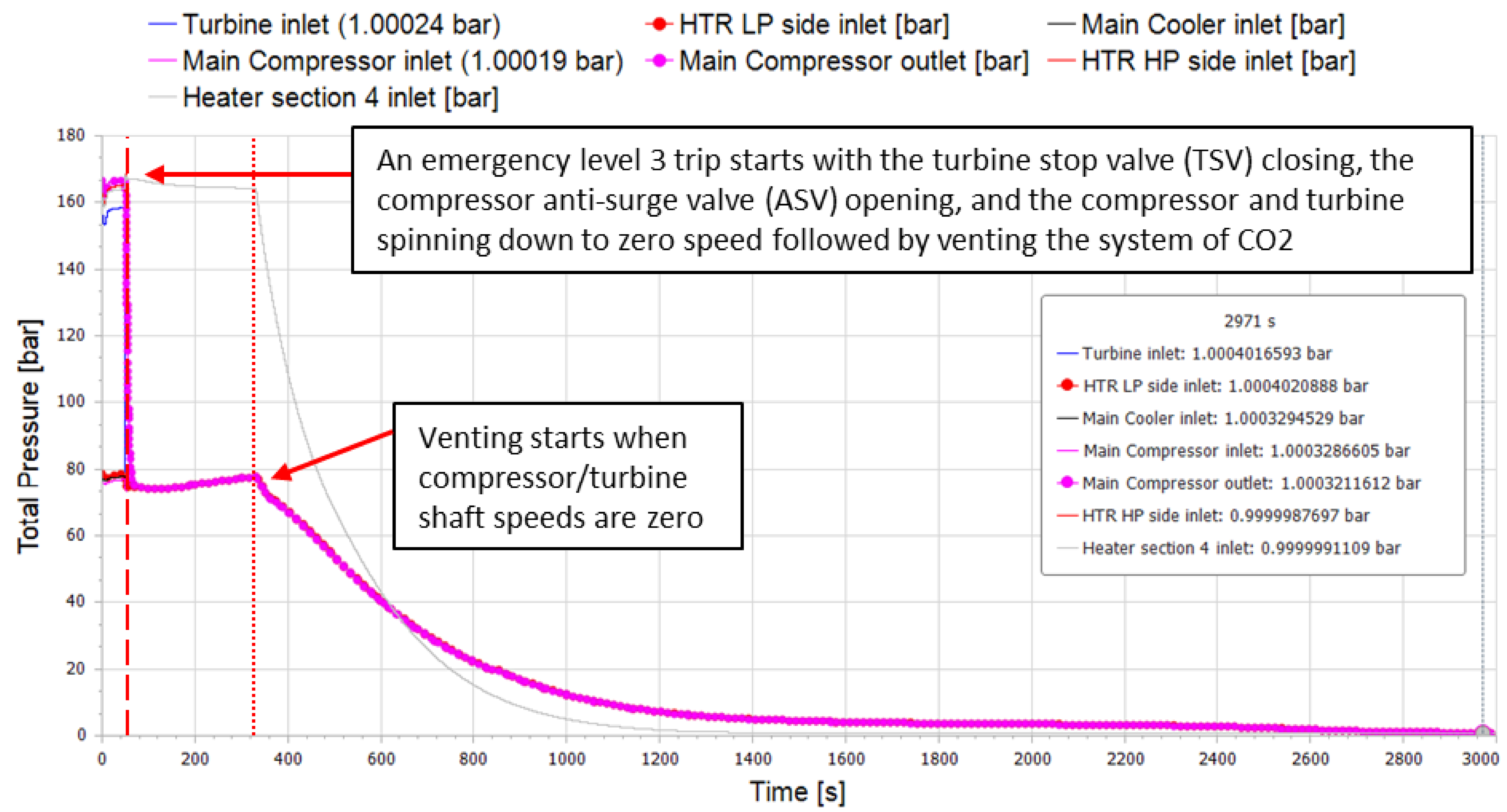
- One purpose of the dynamic model is to study and evaluate control methods and operational procedures for various scenarios
- Scenarios simulated include:
  - Nominal Startup and Shutdown
  - Load Level Changes
  - Emergency Trips
- One example is the Level 3 Emergency Trip simulation and results
  - A Level 3 Trip is a manually activated shutdown trip sequence via the Emergency Shutdown (ESD) button
  - It is intended to completely and rapidly de-energize the plant

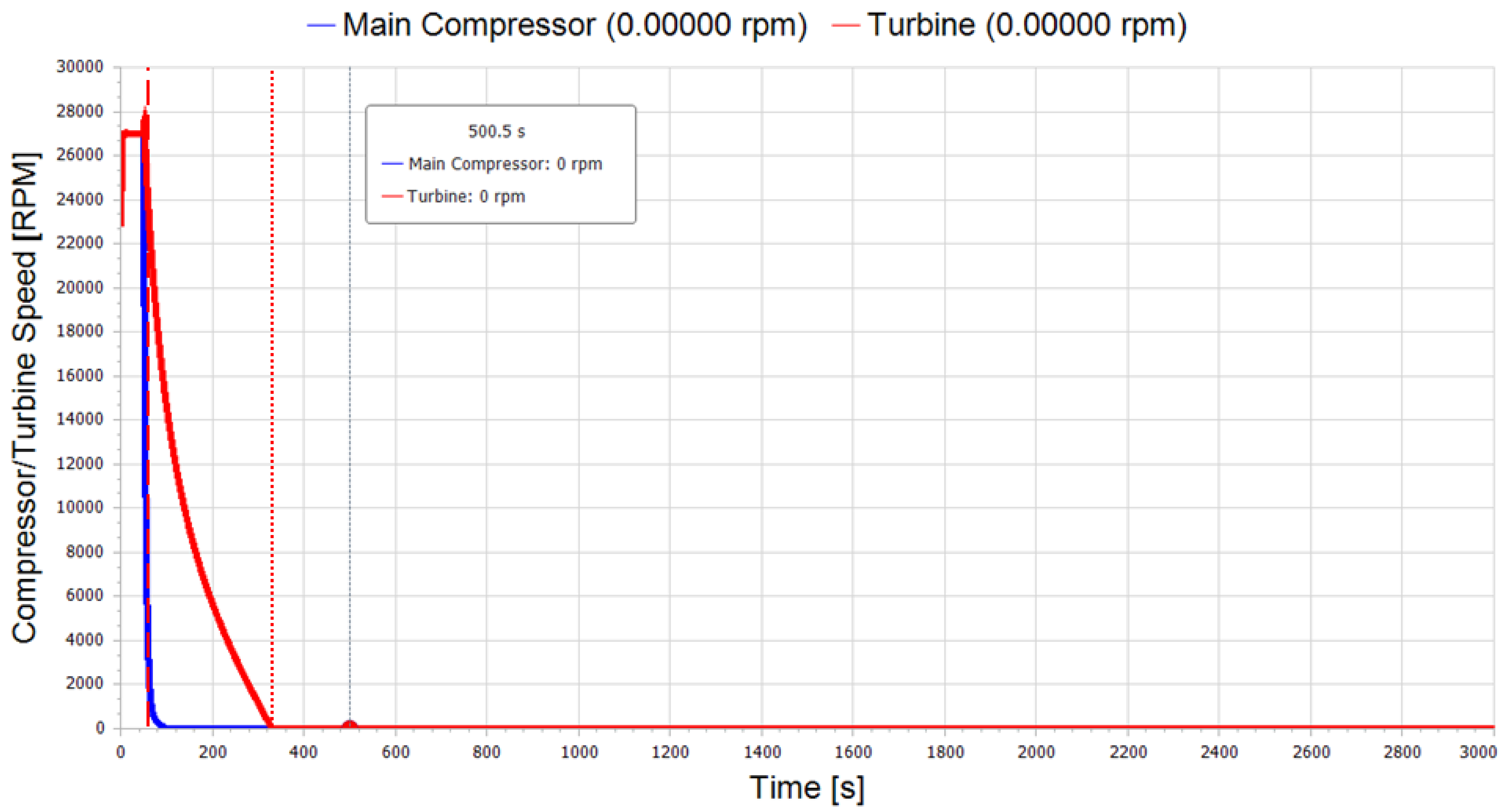


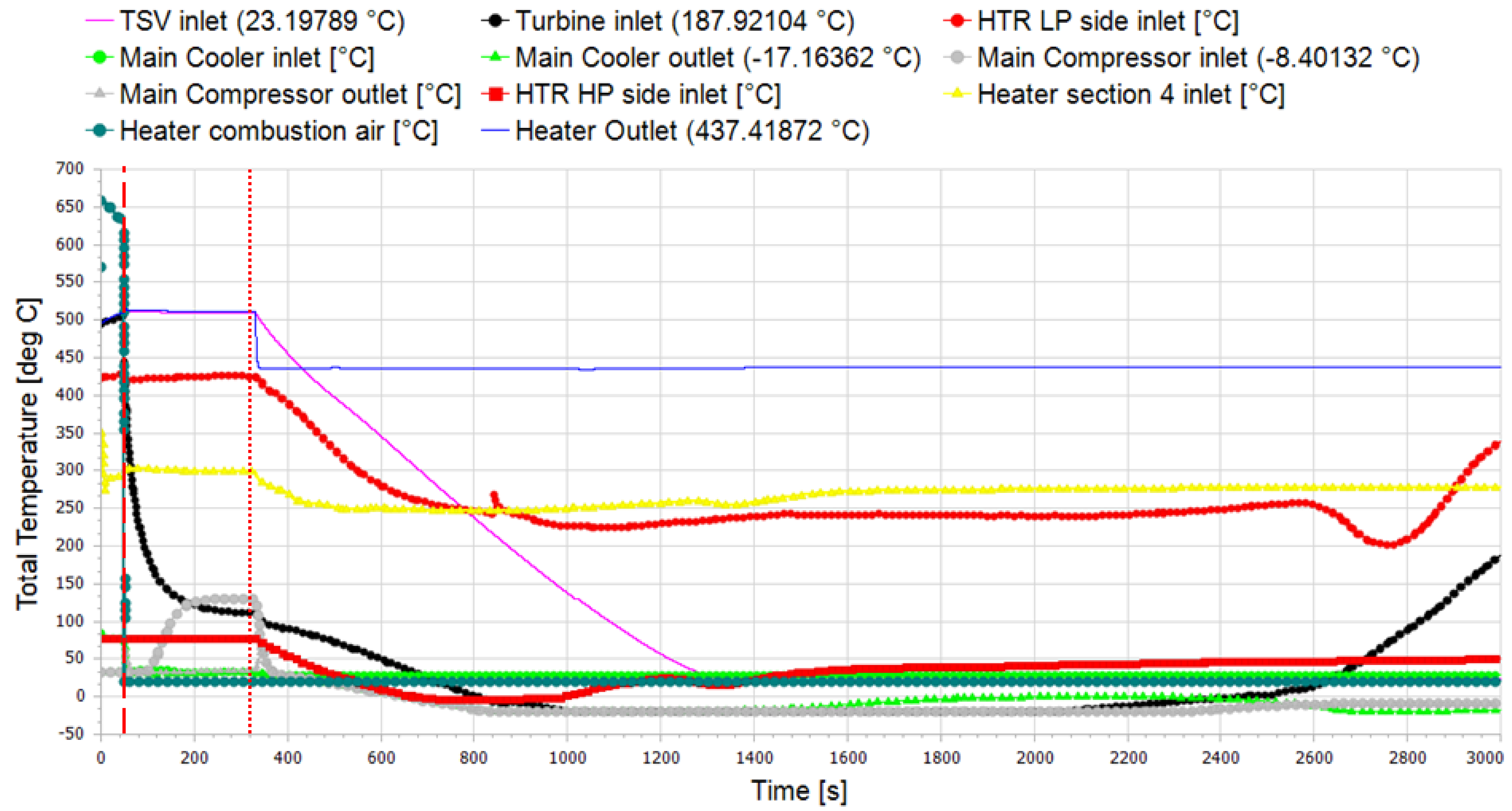
Level 3 Emergency Trip Valve Sequence

Results of Dynamic Model: Emergency Trip L3

- These plots illustrate the shutdown sequence and system response
  - Showing Turbine and Compressor speeds, system pressures and temperatures
- Simulation verifies all requirements are satisfied with current model assumptions

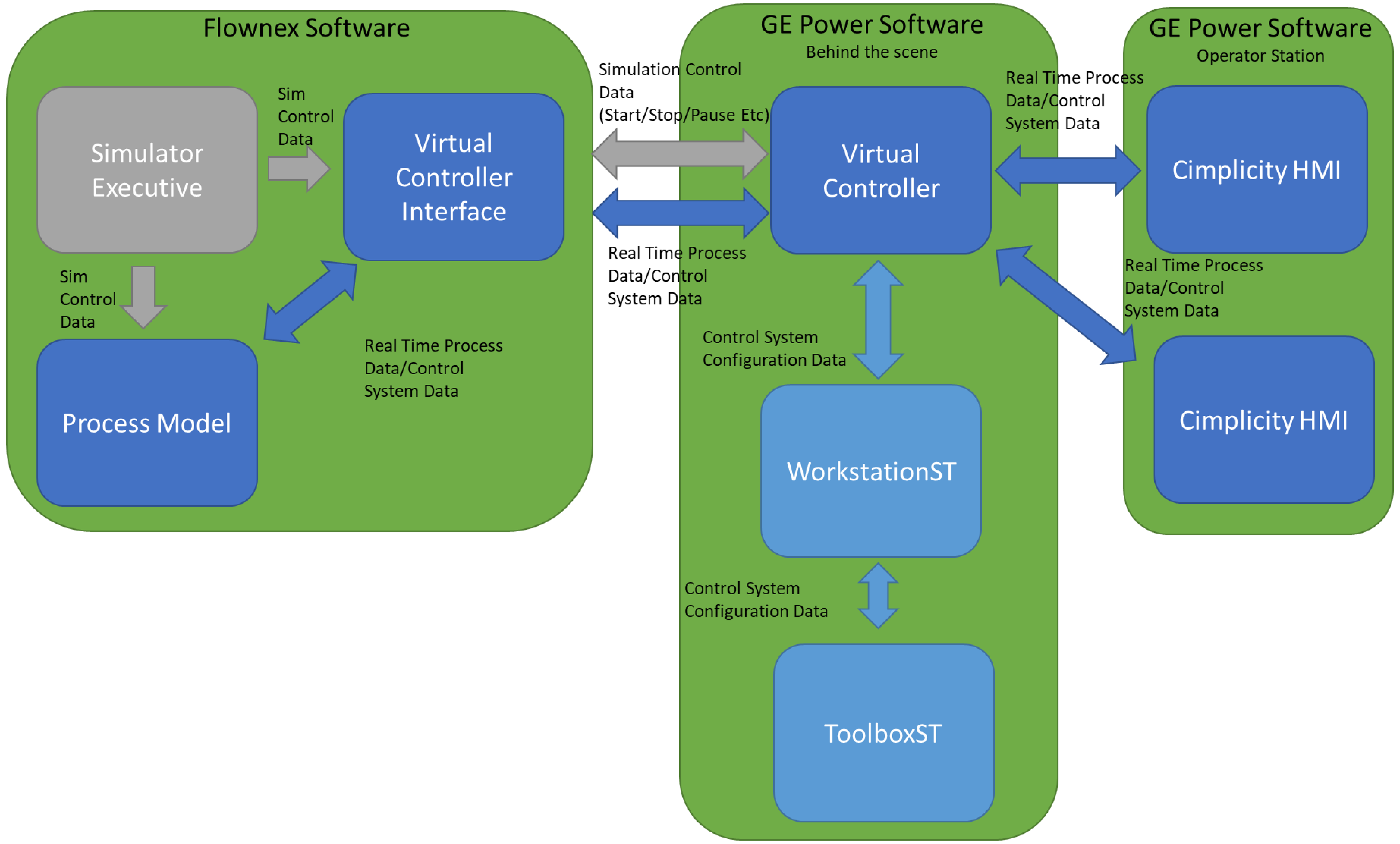






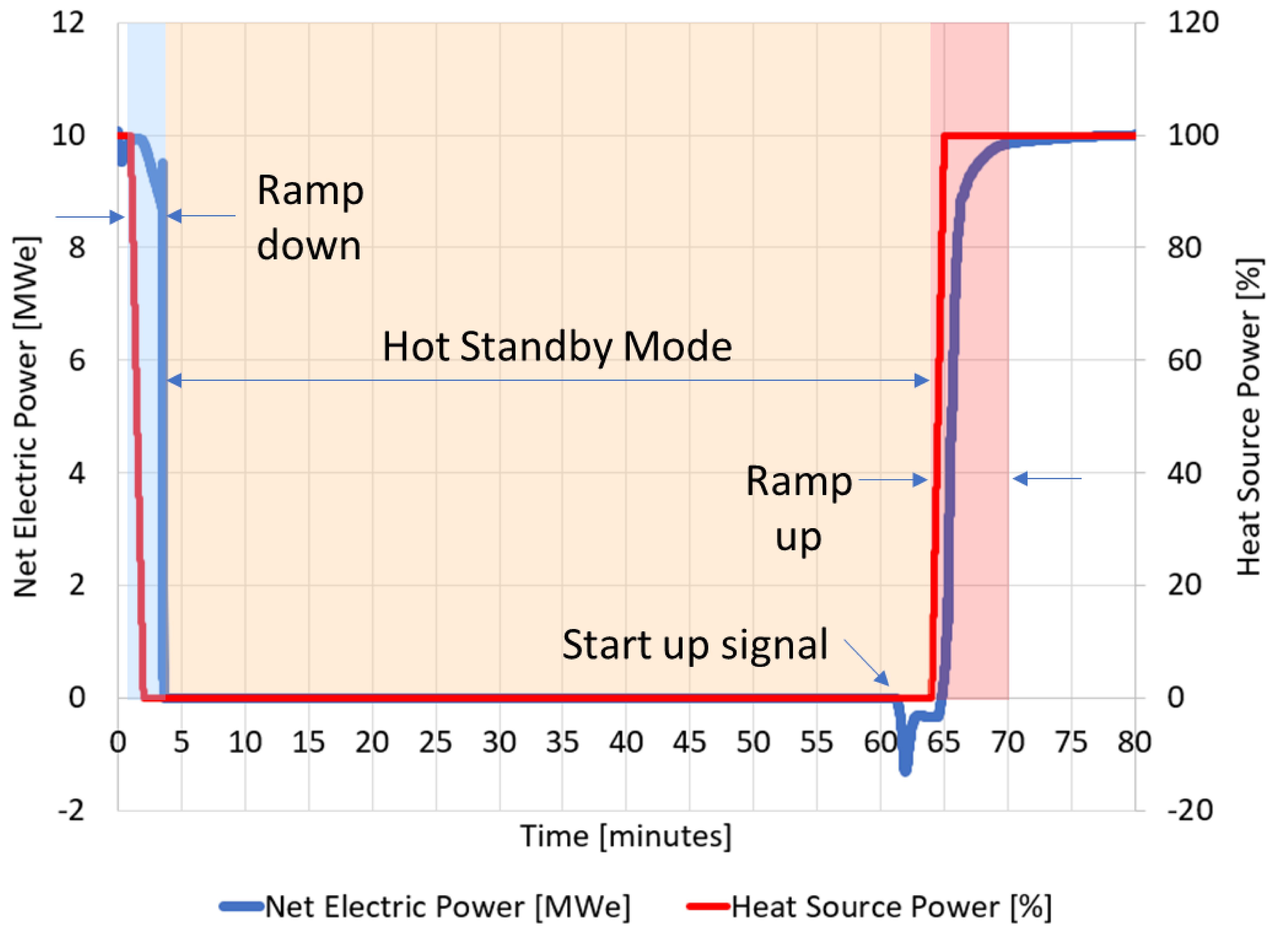
Applications of the Dynamic Model: Implementation of Digital Simulator

- A virtual digital Simulator has been developed for the STEP facility
- The Simulator development was completed in 2022, but has been paused with plans to reinitiate the simulator during RCBC commissioning
- The Simulator will be used during operational planning, preparation of operating procedures and operator training



Applications of the Dynamic Model: External Applications

- The dynamic model was successfully used to predict transient shutdown and startup events in a sCO2 demonstration plant
- This demonstration is to simulate a pulsed input: 3-hour at power, 1-hour off
  - Power generation pattern expected for the United Kingdom Atomic Energy Authority (UKAEA)
- Observations:
  - System shutdown is < 5min, paced by the inertia of the rotating equipment
  - Power-Off: hot condition
  - Startup is < 5min, paced by the inertia of the rotating equipment
- Please refer to paper “Evaluation on the rapidity of sCO2 cycle power up and down events using the STEP dynamic simulation model,” authored by M. McDowell and J. Acres



Questions?

References

1. Marion, J., Kutin, M., McClung, A., Mortzheim, J., Ames, R. (2019) "The STEP 10 MWe sCO2 Pilot Plant Demonstration", *Proc. ASME Turbo Expo GT2019-91509,* Phoenix, AZ.
2. 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.
3. Flownex® version 8.2.0.1735
4. Follett, W. (2022) "DOE Research Performance Progress Report: Supercritical Carbon Dioxide Pilot Plant Test Facility"
5. McDowell, M., Acres, J. (2024) "Evaluation on the rapidity of sCO2 cycle power up and down events using the STEP dynamic simulation model", *The 8th International Supercritical CO2 Power Cycles Symposium*, San Antonio, TX.