Dynamic Modeling for the 10 MWe sCO_2 Test Facility Program

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Information Contained Herein subject to terms of DE-FE0028979

Outline

> STEP Program and Objectives
> Steady State and Transient Modeling
> Component Implementation
> Startup Analysis
> Shutdown Analysis
> Questions?

Supercritical Transformation of Electrical Power (STEP) Program and Objectives

STEP DEMO

> DOE NETL funded program to design, construct, and build a 10 MWe net sCO_2 Brayton cycle test facility

Main Objectives

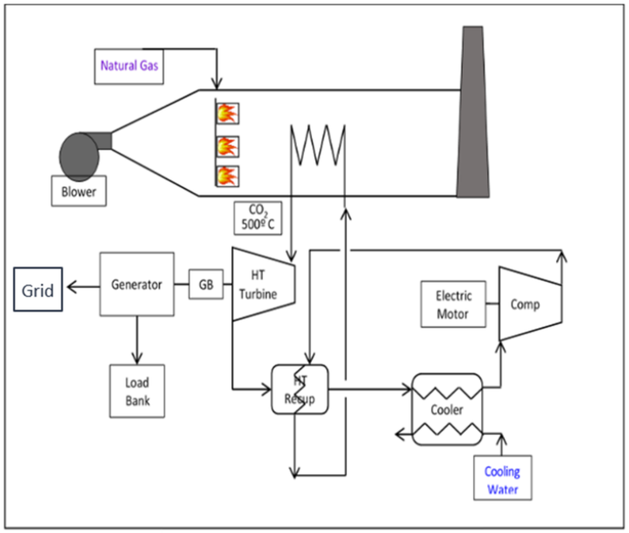
- Verify performance of components (turbomachinery, recuperators)
- Demonstrate operability of sCO2 cycle, Simple cycle and Recompression Brayton Cycle (RCBC)
- Demonstrate the performance and pathway for a cycle efficiency > 50% for large scale applications (>100 MWe)
- Show the potential for producing a lower cost of electricity in relevant applications

System Modeling

STEP DEMO

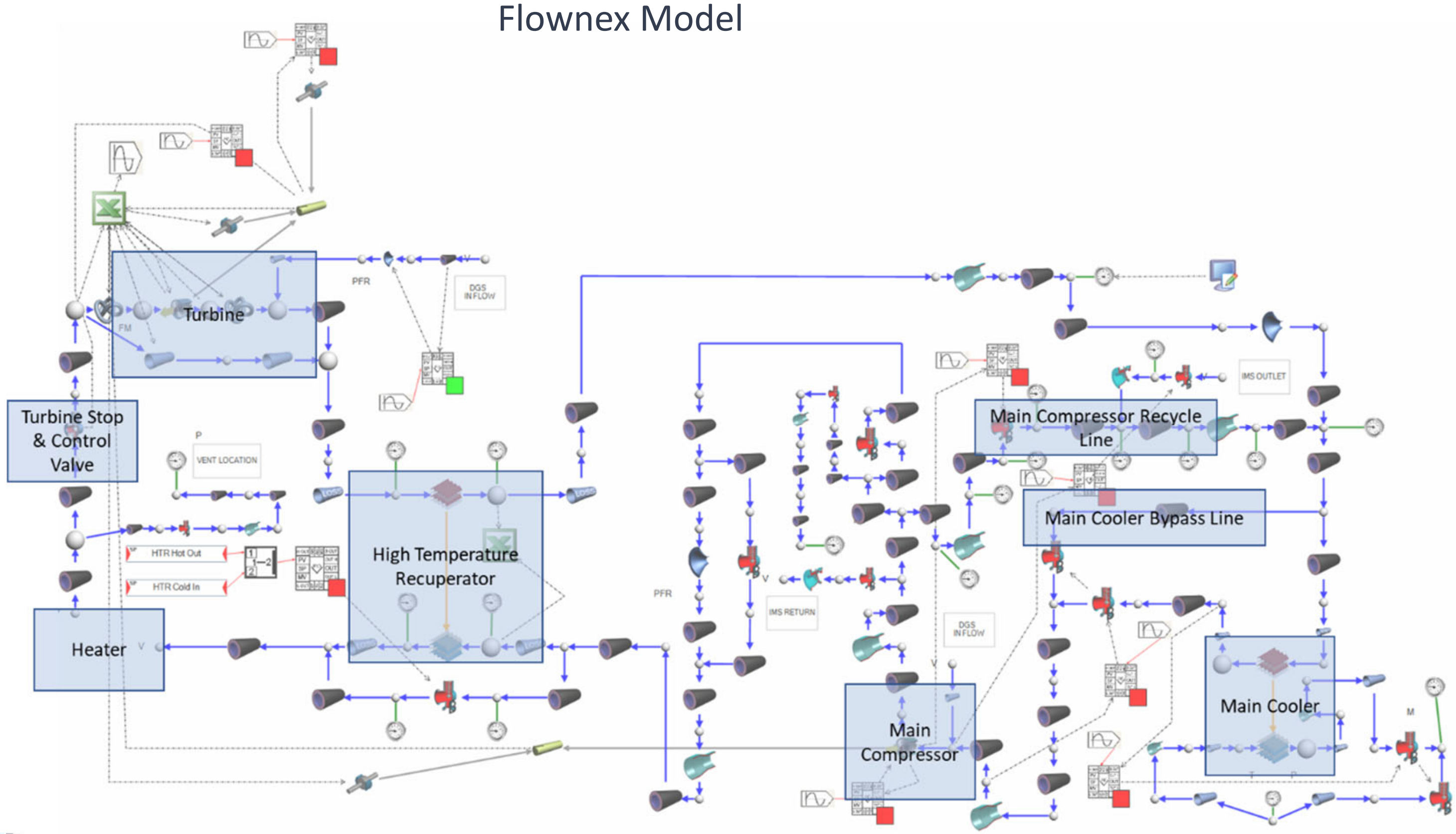
- Steady state and transient analysis performed using Flownex software
- 2 models: one for Simple Cycle and one for RCBC configurations
- sCO2 properties are taken from NIST REFPROP
- Custom component models have been created and benchmarked against vendor predicted performance data
- Various transients 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

Simple Cycle Flownex Model

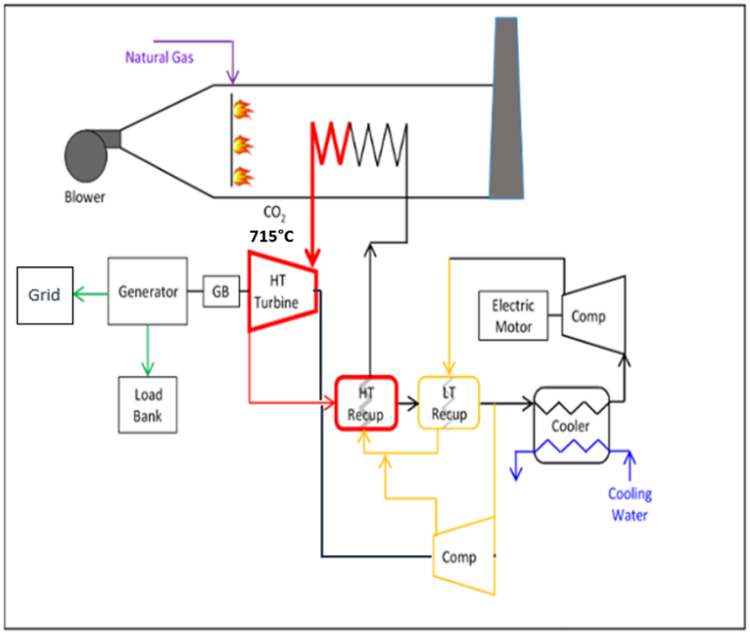


Simplified Diagram

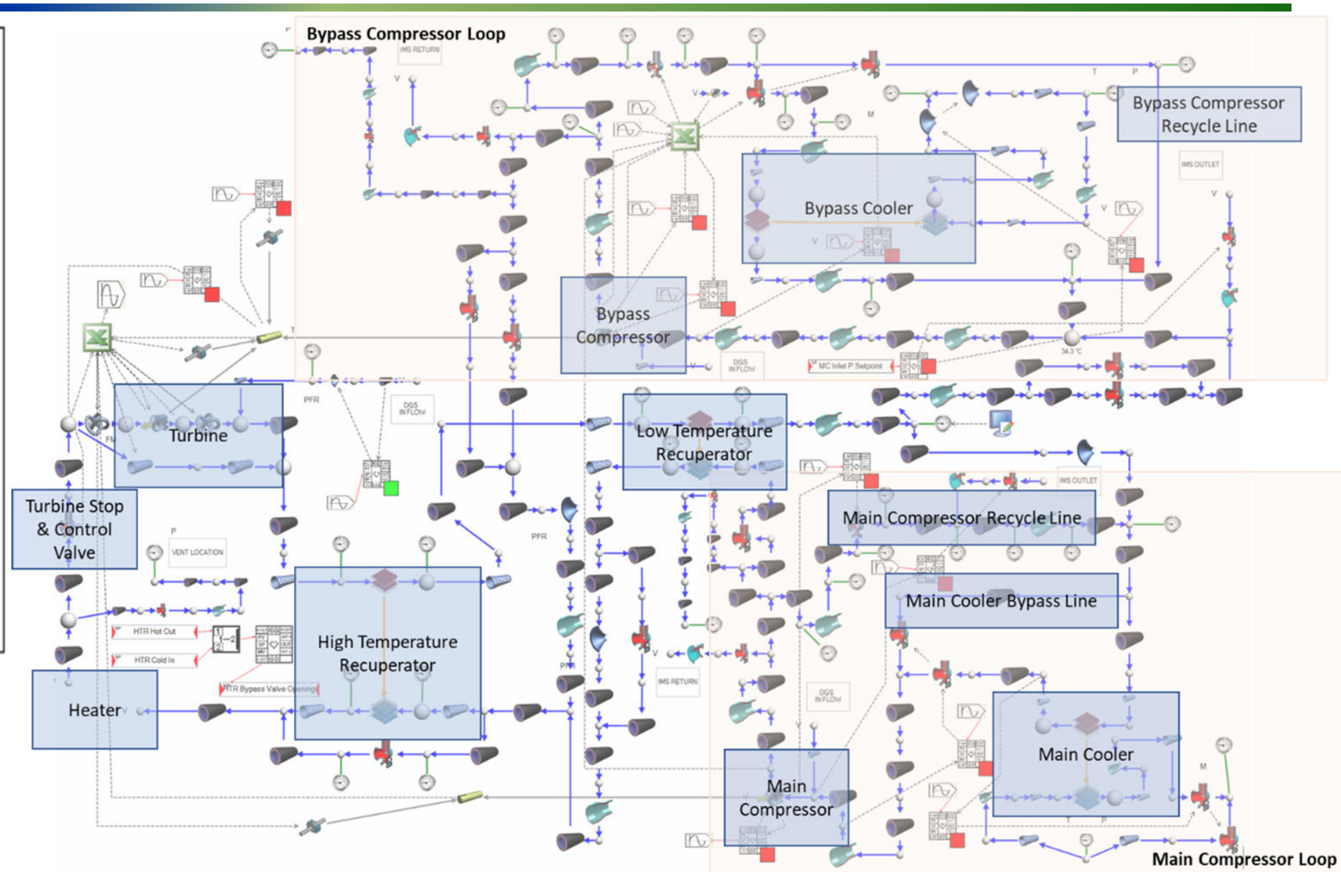
Flownex Model



RCBC Cycle Flownex Model



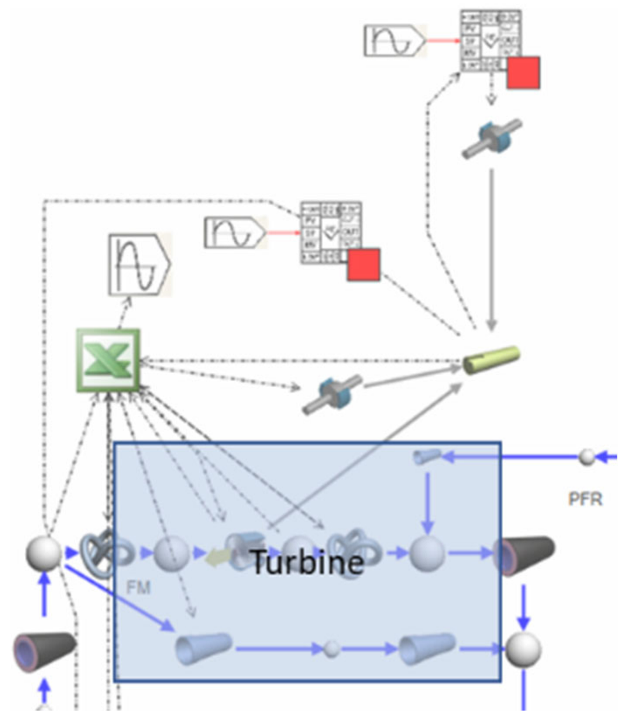
Simplified Diagram



Flownex Model

Component Implementation: Turbine

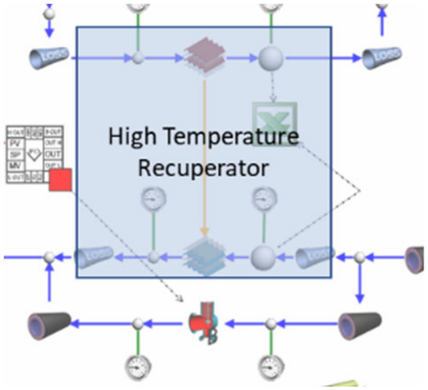
- STEP turbine is modeled through a combination of Flownex elements linked to a spreadsheet
- Spreadsheet houses calculations such as:
  - Turbine flow function
  - Balance piston leakage
  - Inlet and exit pressure losses
- Dry gas seal flows coming from the IMS are modeled

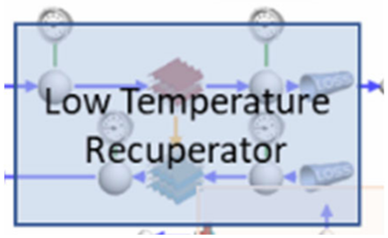


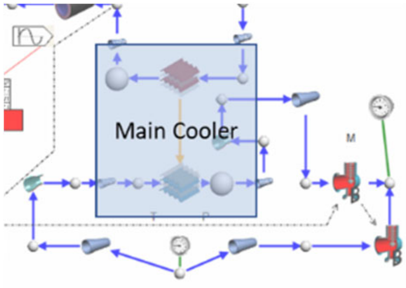
Component Implementation: Recuperators

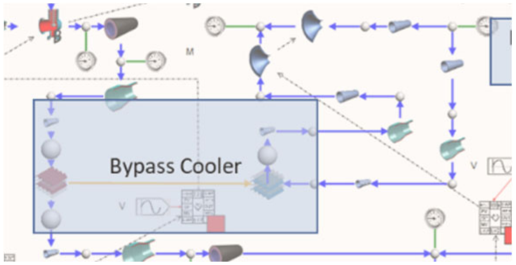
> High temperature recuperator, low temperature recuperator, main and bypass coolers are modeled using plate heat exchanger elements with customized heat transfer correlations

> Error deltas were <2% in predicted outlet temperatures and <0.2 bar in calculated pressure drops



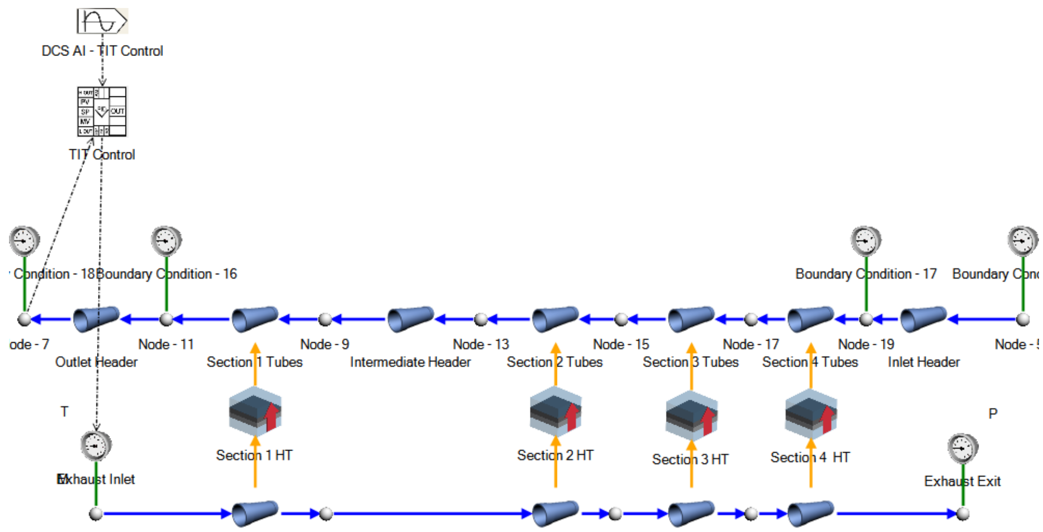






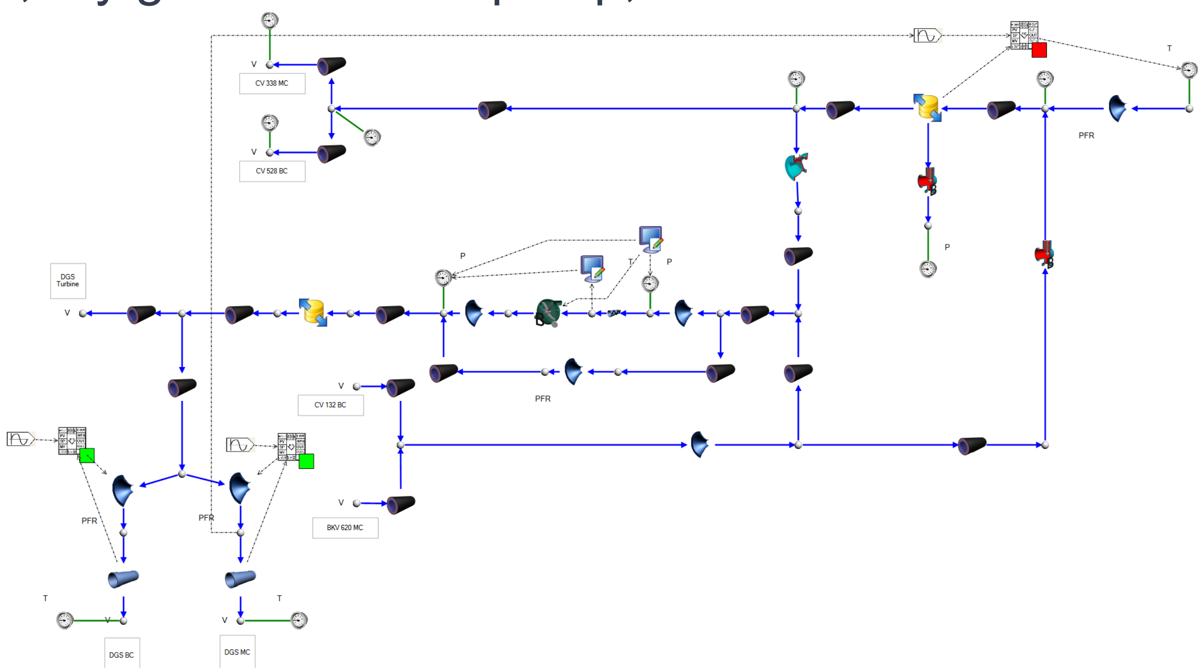
Component Implementation: Heater

- 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: Inventory Management System (IMS)

> IMS consists of a liquid CO2 fill tank and vaporizer (not modeled), vapor storage tanks and vent, dry gas seal boost pump, and a buffer tank



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
  - Flownex originally setup to only handle corrected flow parameters
  - Vendor compressor maps using real gas properties incorporated

Startup Analysis

> Startup of both loop configurations modeled

> General Results:

Configuration	Startup Time	Initial Condition	Final Condition
Simple Cycle	7 hours	50°C, 20 bar	500°C, 217 bar
RCBC	10 hours	50°C, 20 bar	715°C, 250 bar

> Current rate limiter: heater ramp rate

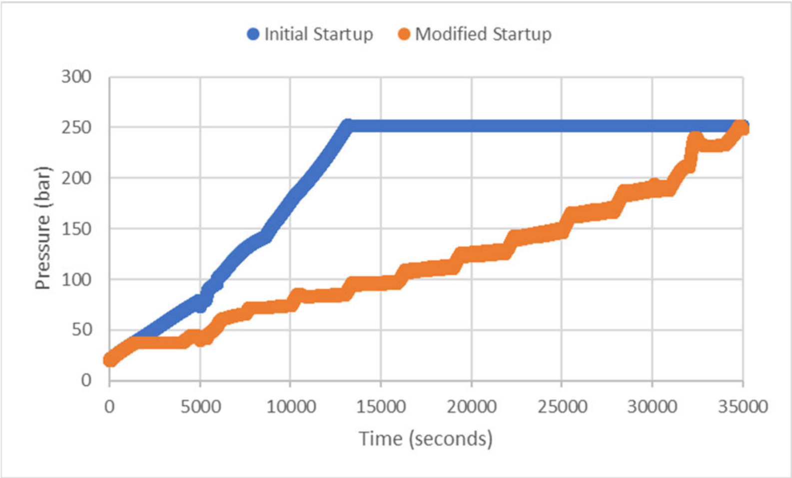
– Further stress analysis on heater could determine if a faster thermal ramp rate is allowable, which will reduce startup times

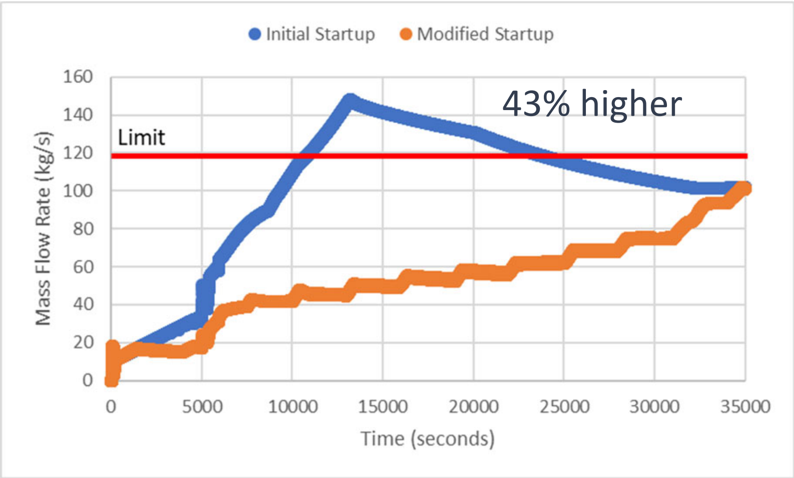
> Main focus of startup analysis: how we start up the system, control methodology, valve sequencing

Startup Analysis:
IMS Control Impact on Flow Rates and Pressure

STEP DEMO

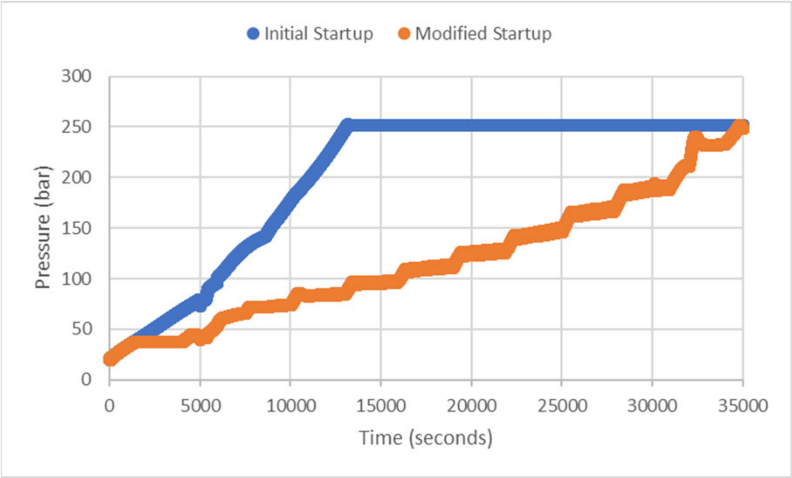
- Our initial methodology of filling the loop was to fill the system with CO_2 until you've reached system pressures and then remove CO_2 if needed
- Preliminary results showed very high peak flow rates that exceed equipment allowable design limits

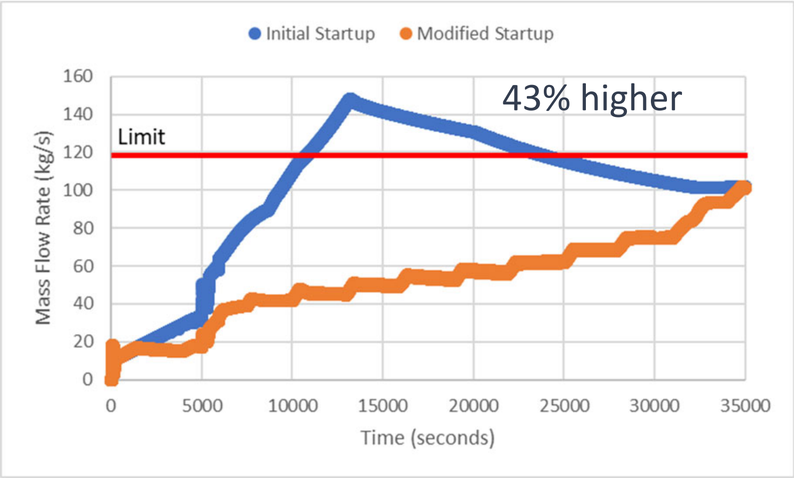




Startup Analysis:
IMS Control Impact on Flow Rates and Pressure

- To reduce this peak flow rate, we modified startup to slowly increase the system pressure by slower addition of mass through the IMS to control compressor suction side pressures
- From this we learned the impact of IMS control on system pressure during startup

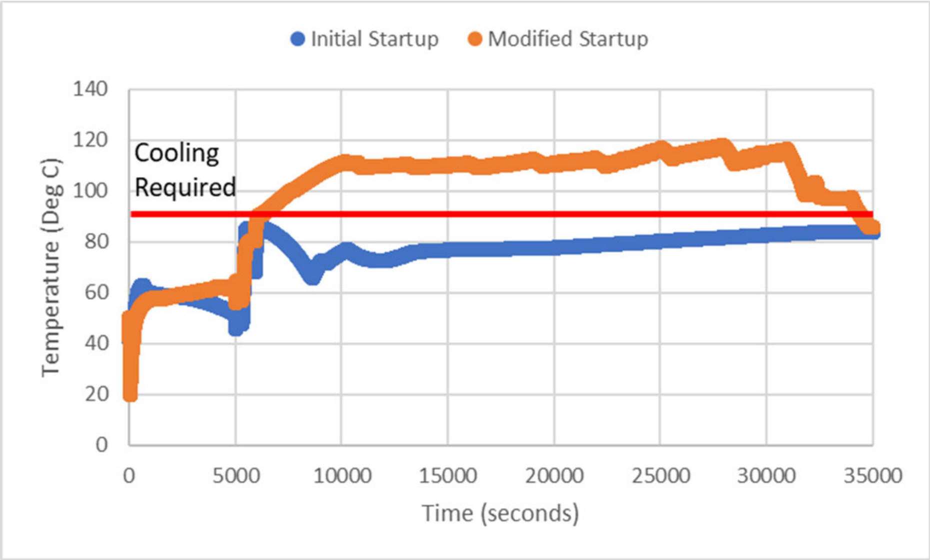




Startup Analysis:
IMS Control Impact on Bypass Cooling Requirements

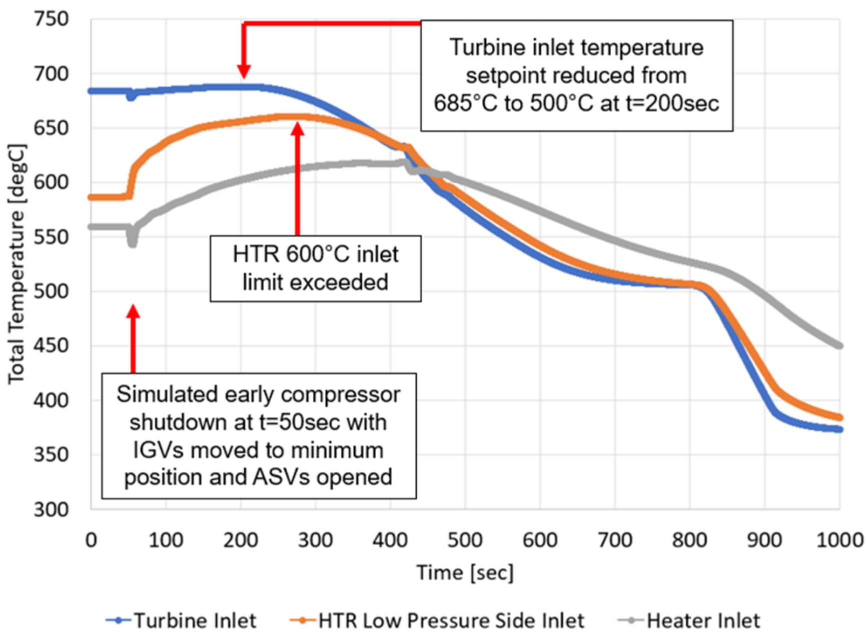
STEP DEMO

- The initial startup simulation showed CO2 temperatures exiting the LTR low pressure side and entering the bypass compressor loop were low enough such that cooling was not required by the bypass cooler
- With the modified startup, cooling is now required by the bypass cooler
  - This simulation required ~1 MWth of cooling



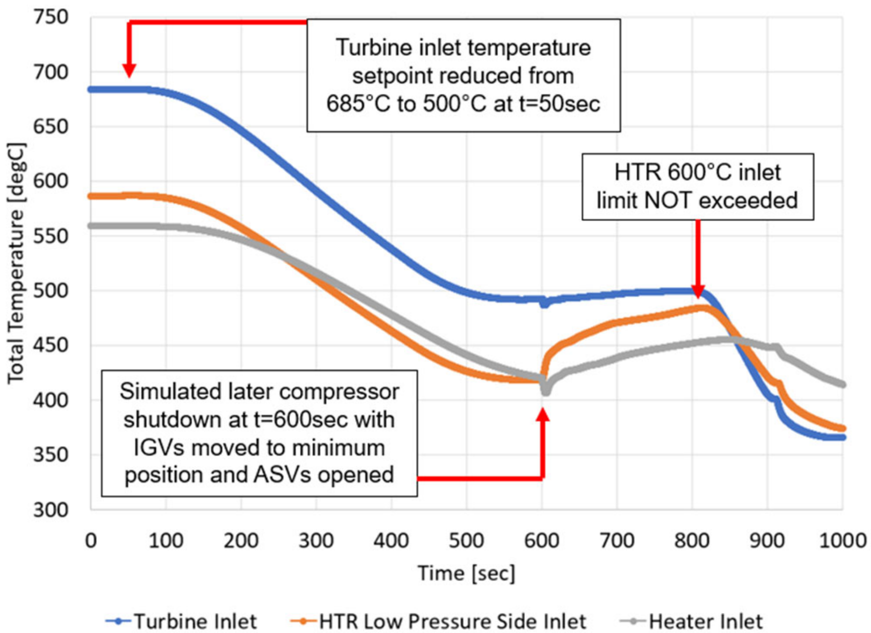
Using the IMS to vary mass and heat additions and flowrates at various times during startup allows for optimization of bypass cooler requirements while respecting system mass flow rate limits

Shutdown Analysis: Shutdown Sequencing



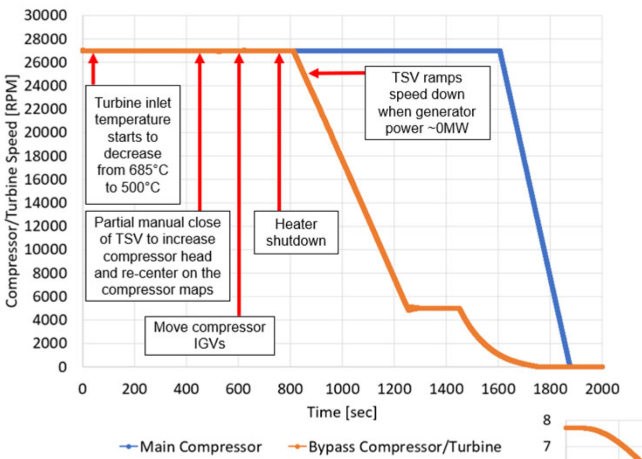
- Shutdown of both loops modeled
- RCBC initial shutdown sequence resulted in HTR low pressure side inlet temperature exceeding 600°C limit
- Compressor inlet guide vanes move to their minimum position and anti-surge valves open prior to reduction in turbine inlet temperature
- Turbine and HTR flow decrease, turbine power also decreases → reduced turbine speed, CO_2 flowing through HTR remains hotter as less heat is extracted from expansion through the turbine

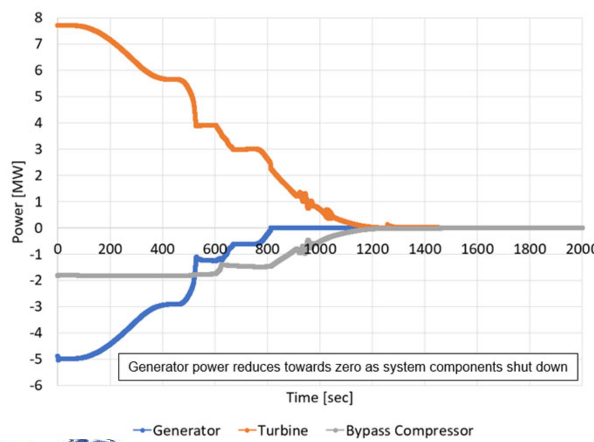
Shutdown Analysis: Shutdown Sequencing



- RCBC shutdown was run again but with heater firing reduced prior to moving the IGVs and ASVs
- HTR low pressure side inlet temperature limit no longer exceeded

Shutdown Analysis: Compressor Map Operation During Shutdown





- RCBC shutdown with turbine inlet temperature decreased before turbine stop valve (TSV) is closed
- Degree of TSV closing affects position on compressor maps
  - Sensitivity run to determine optimal closing position to maintain stable compressor operation
- IGVs then moved to a lessor position to reduce flow and heater was shut down
- All these actions reduced generator load
- TSV then fully closed, main compressor ramped down

Questions?

Thank you