Prediction Methods of Settle Out Conditions and Design in sCO2 Power Cycles

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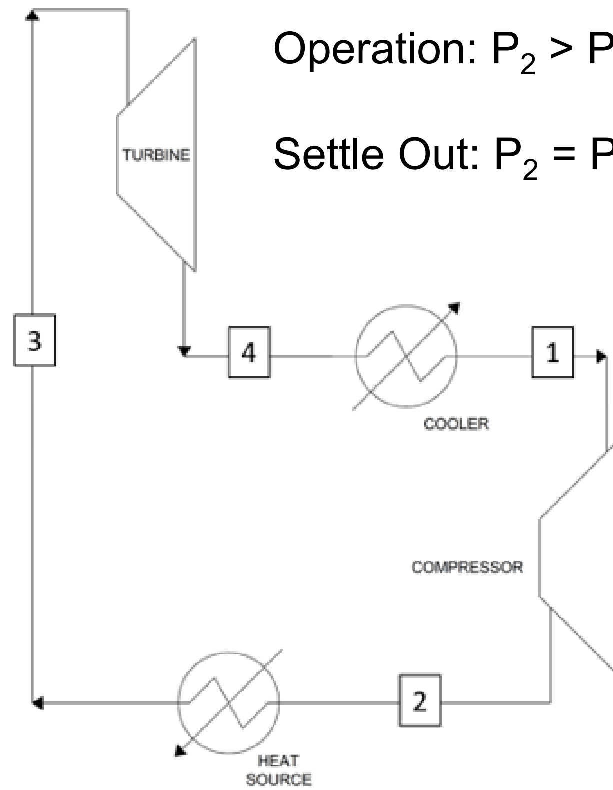
Outline

- Background
- Methods to predict settle out conditions
- Lessons learned from the STEP project
- Questions

Background

- Closed loop design
- Design conditions
  - Defined by operation?
  - Defined by settle out?
- Settle out conditions
  - Pressure
  - Temperature
- Settle out flow directions

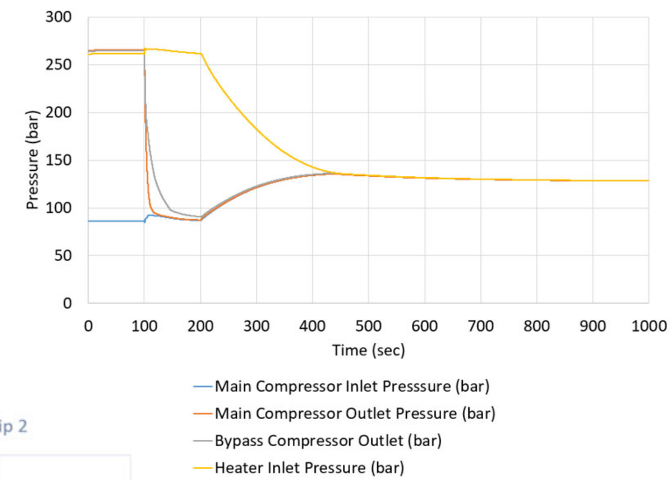


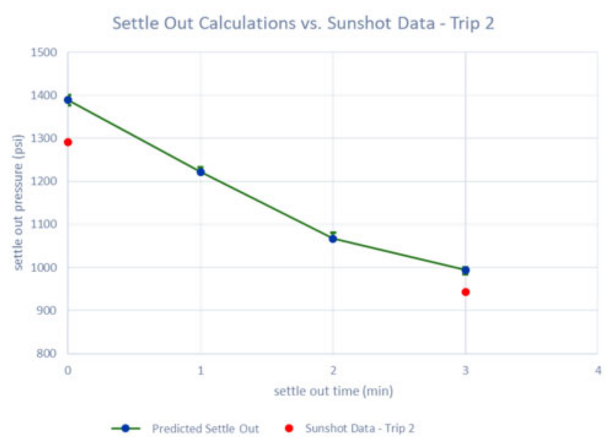
Operation: $P_2 > P_3 >> P_4 > P_1$

Settle Out: $P_2 = P_3 = P_4 = P_1$

Methods to Predict Settle Out Conditions

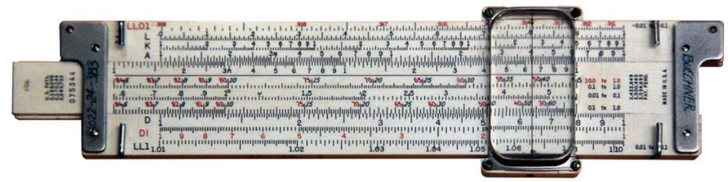
- Transient system model
  - Accurate
  - Expensive
  - Time consuming
- Hand calculations
  - Not as accurate
  - Cost effective
  - Faster cycle time

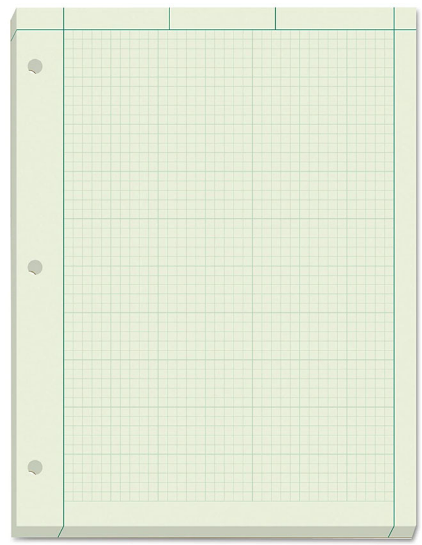


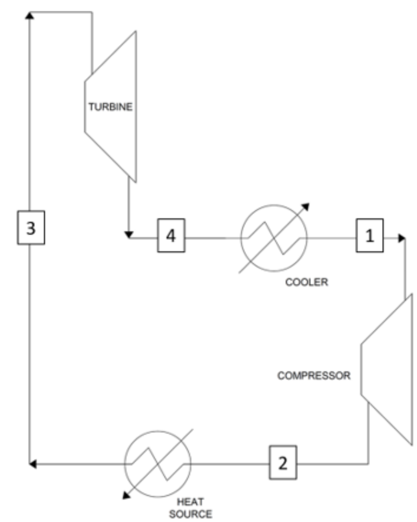


“Hand Calculations”

- Hand calculations
  - Spreadsheet calculations using goal seek to iterate to solutions
  - Divide the system into control volumes with initial conditions
  - Initial conditions generated by steady state system models
  - Control volumes determined from piping model and equipment data sheets.

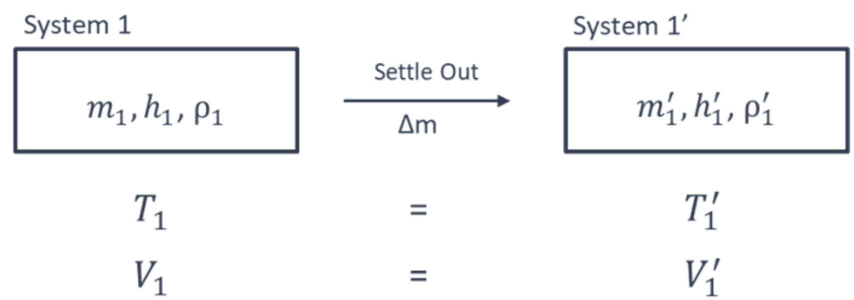






1 – Total Mass & System Temperature

- Each control volume maintains the initial temperature and volume.
- Mass is allowed to migrate across control volume boundaries.
- This assumes that the mass that migrates to another control volume quickly becomes the temperature of the fluid in the new control volume (heat transfer with piping and equipment).
- Initial Temperatures, Pressures, and Mass used to solve for settle out Pressure.

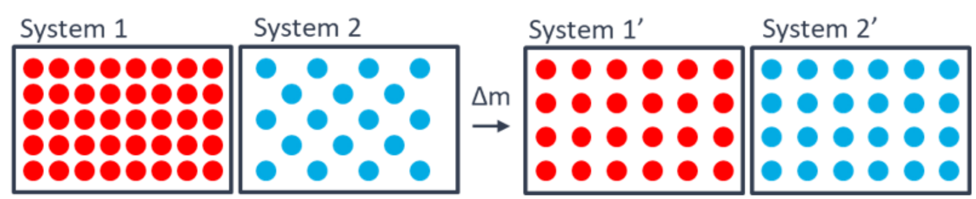


$$P_1' = P_2' = P_3' = P_4' = P_{s.o.}$$

Total Energy **NOT** conserved

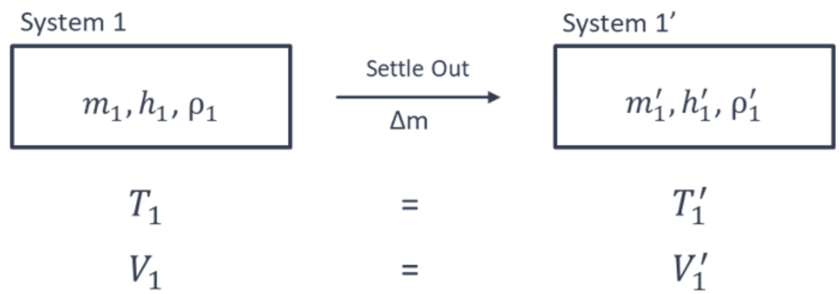
Total Mass is conserved

Total Volume is conserved



2 – Total Energy & System Temperature

- Each control volume maintains the initial temperature and volume.
- Mass is allowed to migrate across control volume boundaries.
- This assumes that the mass that migrates to another control volume quickly becomes the temperature of the fluid in the new control volume (heat transfer with piping and equipment).
- Initial Temperatures, Pressures, and Energy (enthalpy * mass) used to solve for settle out Pressure.



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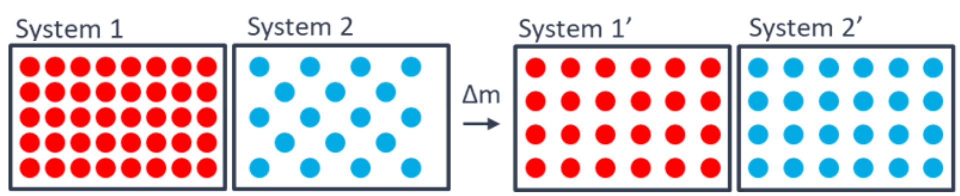


3 – Isenthalpic Expansion & Compression of Control Masses

- Each control volume maintains the initial mass and enthalpy.
- The control volumes changes size but the fluid doesn't mix with other control volumes.
- This assumes that the control volumes are adiabatic, temperature changes from compression or expansion but not heat transfer to piping or equipment.
- Initial masses, and enthalpies used to solve for settle out Pressure.

$$h_1 = h_1'$$

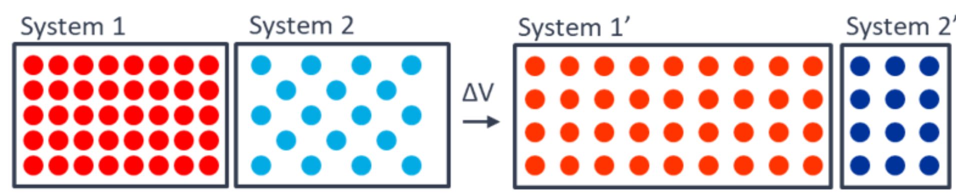
$$m_1 = m_1'$$

$$P_1' = P_2' = P_3' = P_4' = P_{s.o.}$$

Total Energy is conserved

Total Mass is conserved

Total Volume is conserved



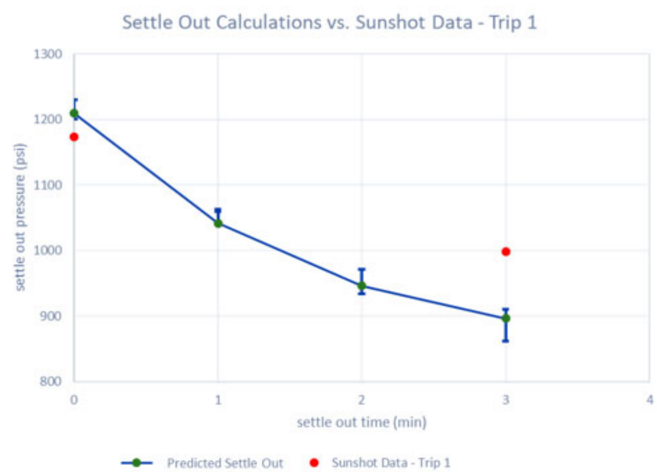
Comparison of Methods

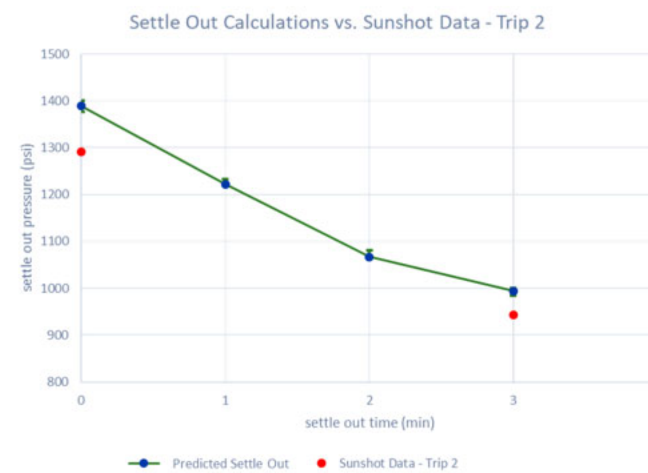
Approach #1	Approach #2	Approach #3
Total Energy **NOT** conserved	Total Energy is conserved	Total Energy is conserved
Total Mass is conserved	Total Mass **NOT** conserved	Total Mass is conserved
Total Volume is conserved	Total Volume is conserved	Total Volume is conserved
$P_{s.o.}$ = 140.5 bar	$P_{s.o.}$ = 167.1 bar	$P_{s.o.}$ = 186.6 bar
ΔH = -488,973 kJ (-17.6%)	Δm =955 kg (+17.4%)	

Approach #3 is the most conservative, predicting the highest settle out pressure.

Approach #3 for SunShot Data

- Isenthalpic Expansion & Compression of Control Masses
- In addition to the immediate settle out condition an effort was made to predict the pressure vs time due to heat loss of the system
- Approach #3 was determined to be conservative, slightly overpredicting the settle out pressure





Settle Out Pressure (psi)	Trip 1	Trip 2
Sunshot Data	1173	1291
Prediction	1209	1389

Approach #3 Equations

$$V_{Total} = \sum_{i=1}^{n} V_i$$

$$\rho_i = f(P_i, T_i)$$
$$h_i = f(P_i, T_i)$$
$$m_i = \rho_i * V_i$$

Goal Seek delta volume to zero by changing settle out pressure. Using Refprop in the spreadsheet to lookup CO2 properties.

$$\rho_i' = f(P_{Settle\ Out}, h_i)$$

$$V_i' = \frac{m_i}{\rho_i'}$$

$$\Delta_{Volume} = \sum_{i=1}^{n} V_i - \sum_{i=1}^{n} V_i'$$

$h_1 = h_1'$

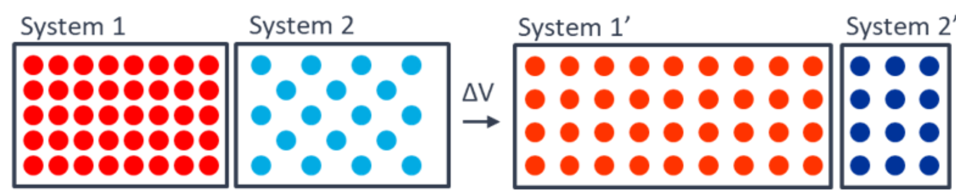
$m_1 = m_1'$

$$P_1' = P_2' = P_3' = P_4' = P_{s.o.}$$

Total Energy is conserved

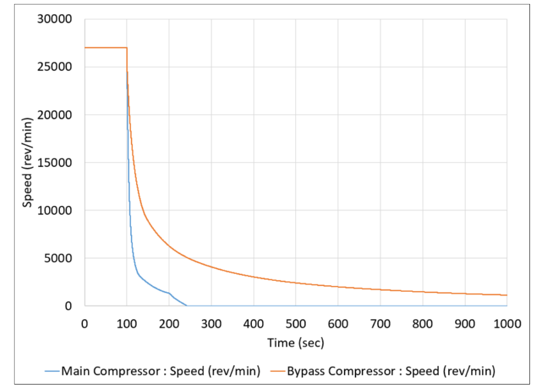
Total Mass is conserved

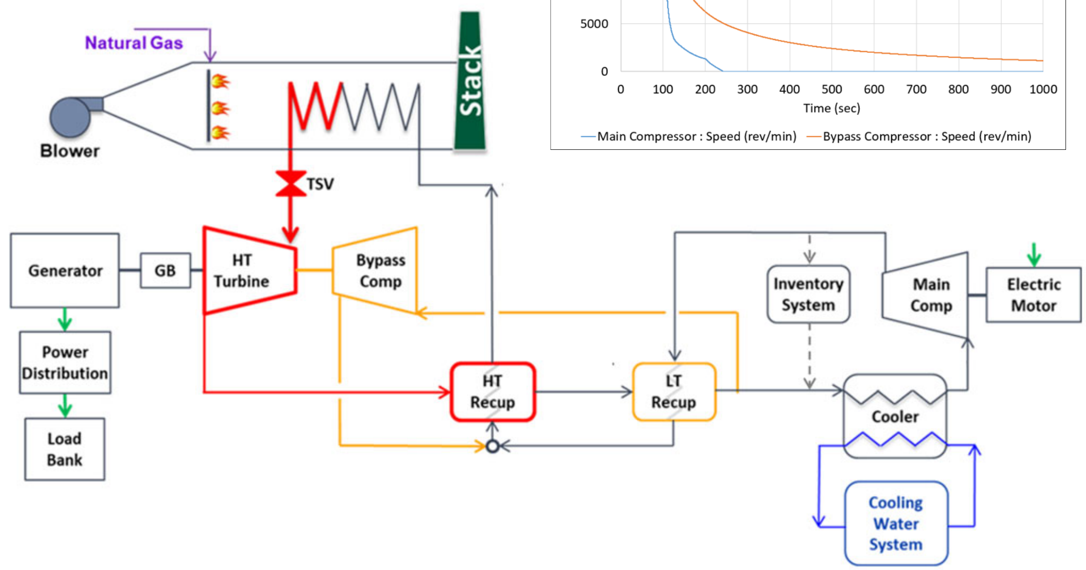
Total Volume is conserved



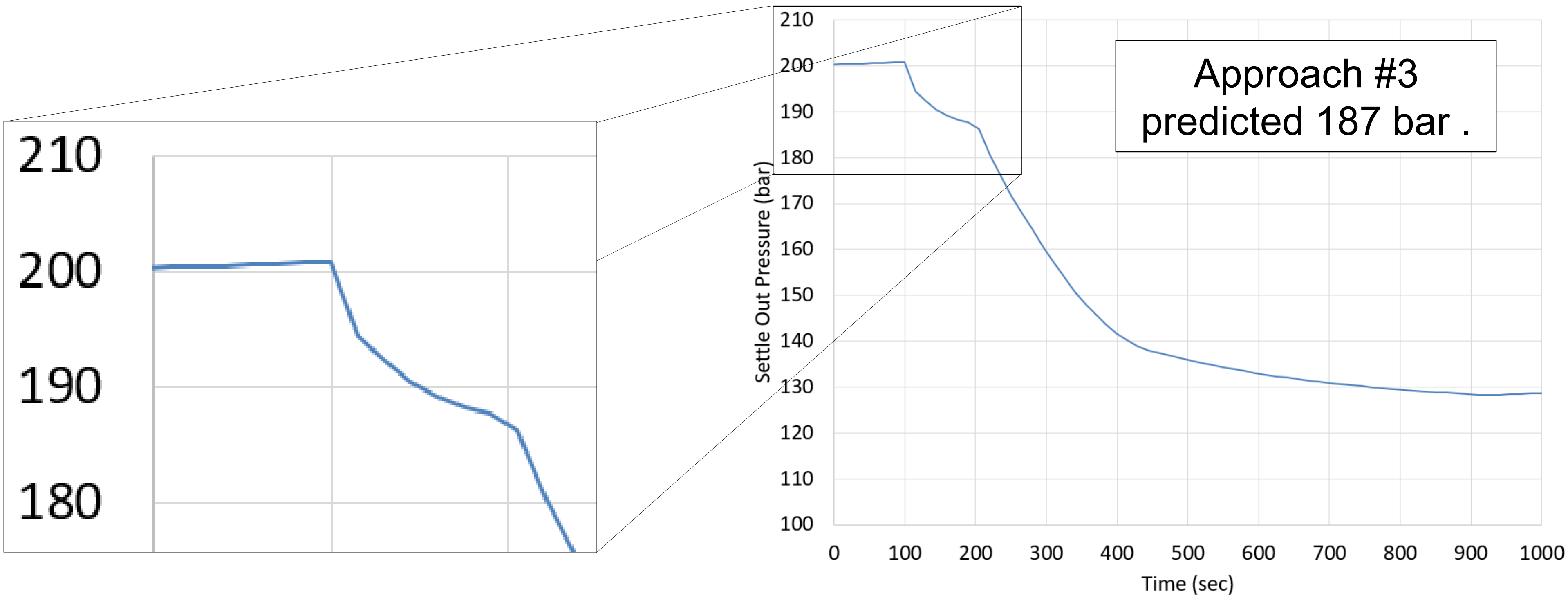
Transient System Model

- A Flownex model of both the Simple Cycle and the Recompression Closed Brayton Cycle has been developed.
  - The focus of the model is to predict transient operations, startup, shutdown, load changes
  - The transient model has much more detail than the hand calculation approach (compressor spin down, valve timing, etc.)
  - No energy transfer to the ambient environment is modeled





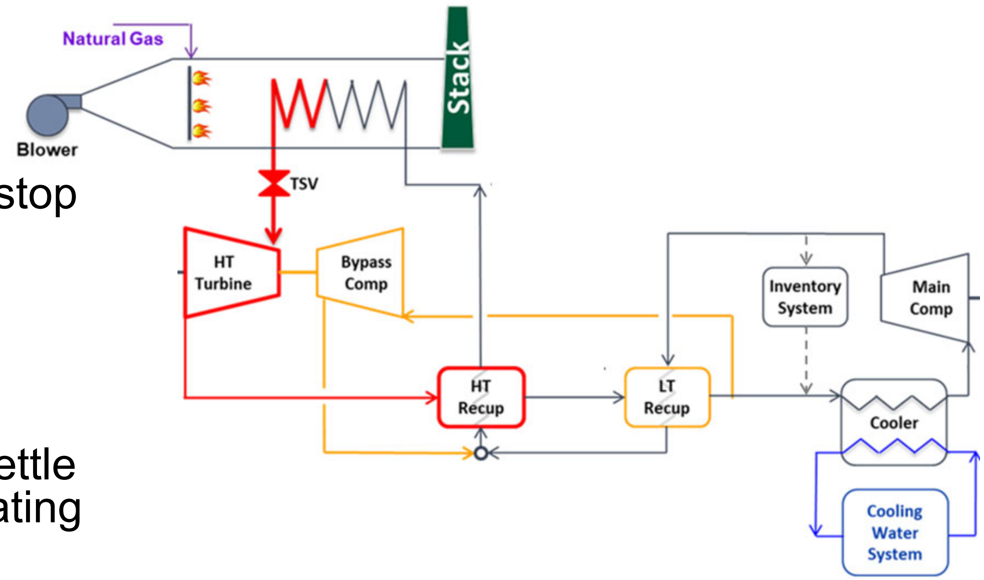
Transient System Model of a Trip with Full Settle Out



Lessons learned from STEP

- The heater volume had a huge impact on the volume ratio, and lead to a higher settle out pressure.
  - Keep an eye on the loop volume ratio during design.
- Hot CO2 between the heater and the turbine stop valve has to be cooled before backflowing through the loop.
  - Consider the direction of flow and temperature migration during a settle out event.

- The STEP team is incorporating a real-time settle out pressure prediction based on actual operating conditions using the DCS.
- The STEP facility has designed additional valves to result in a 2 pressure settle out condition.



It is valuable to have both an accurate transient system model and spreadsheet calculations.

Acknowledgments

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- Project Partners
  - GTI
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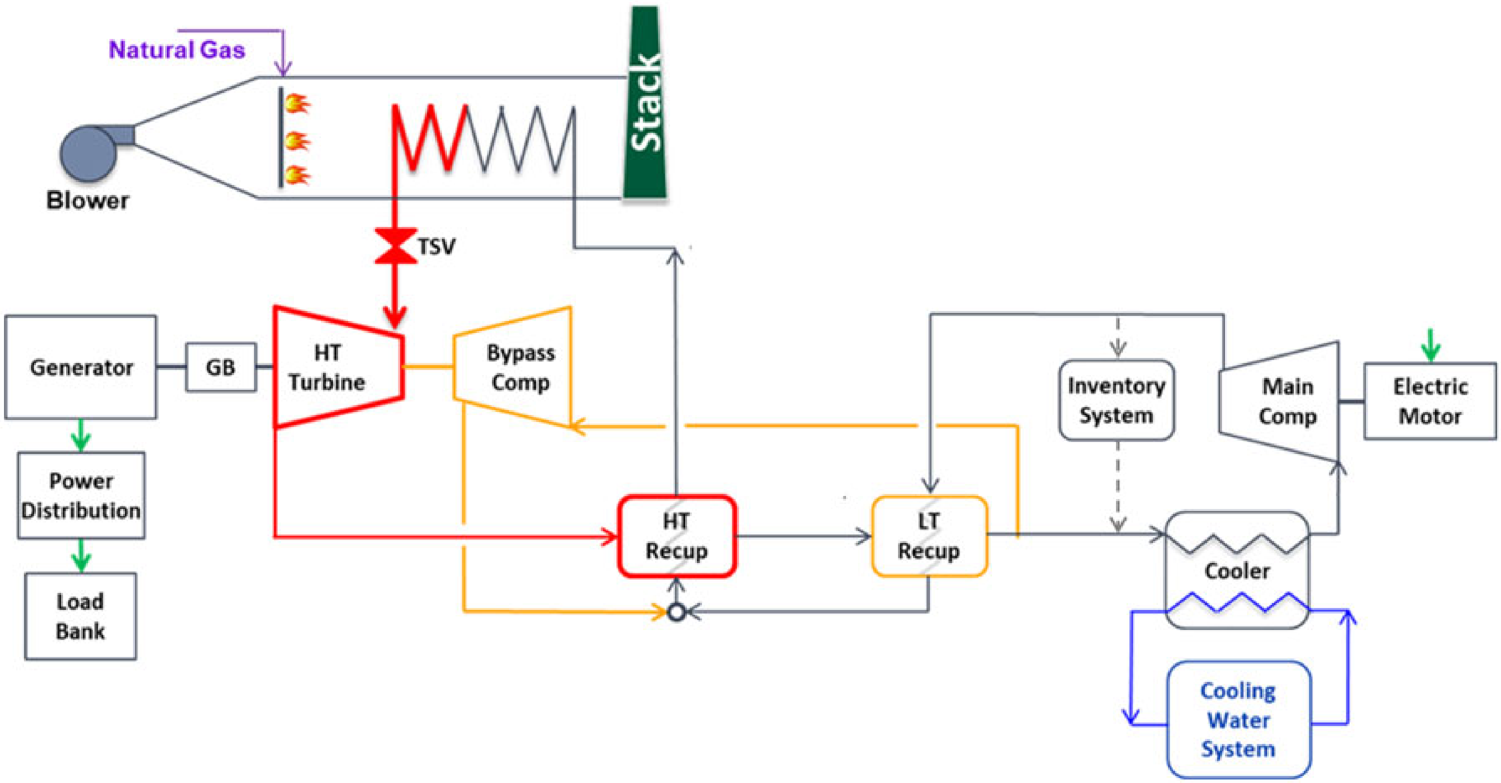
Questions

Thank you for your time.

Backup Slides

RCBC Layout


Natural Gas
Stack
Blower
TSV
Generator
GB
HT
Turbine
Bypass
Comp
Inventory
System
Main
Comp
Electric
Motor
Power
Distribution
HT
Recup
LT
Recup
Cooler
Load
Bank
Cooling
Water
System

Transient Settle Out Pressure