S-CO_2 Brayton Recompression Loop Design and Control

1) Background
2) Recommended Design Features
3) Modeling
   - Strategy
   - IST Model Changes
   - Transient Results

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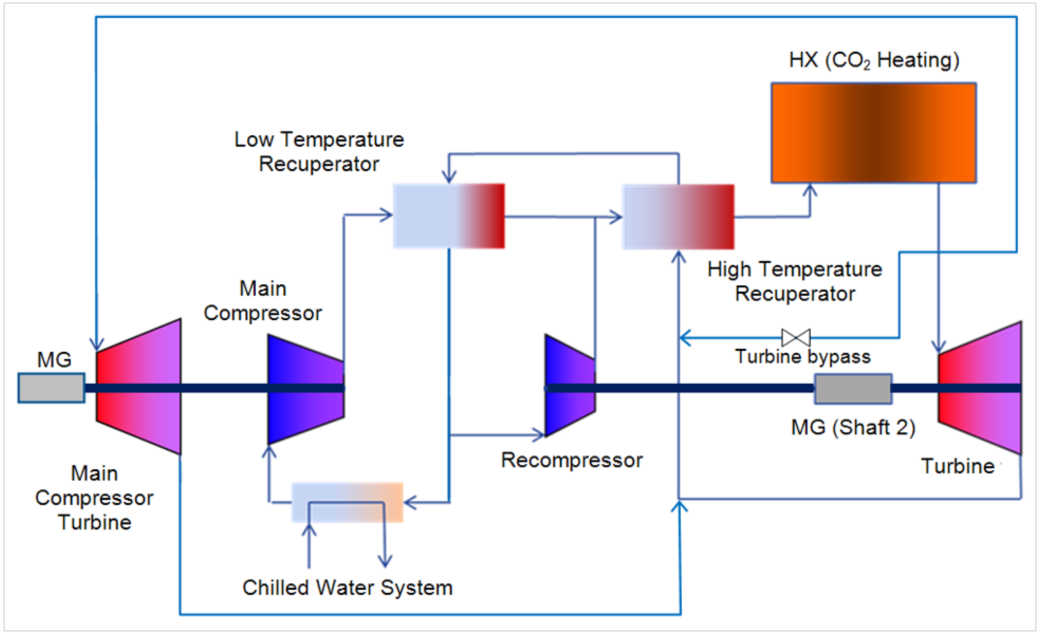
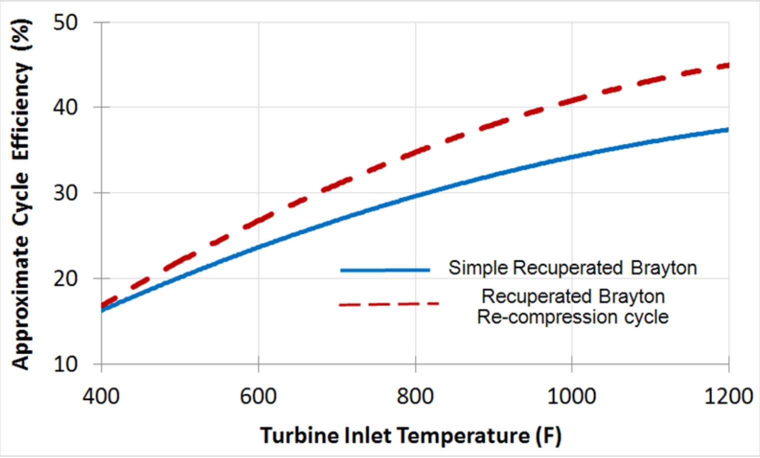
Background

Why Recompression (Advantages):

The Brayton recompression loop utilizes two compressors arranged in parallel to increase cycle efficiency. The additional compressor is used to compress a fraction of the working fluid before energy is removed by the precooler.

Recuperation is split resulting in low and high temperature units. The CO_2 that is compressed before entering the precooler rejoins the main flow path downstream of the low temperature recuperator. By splitting the recuperation duty each heat exchanger will be designed for a lower heat duty and lower temperature drop than the single recuperator in the simple cycle.

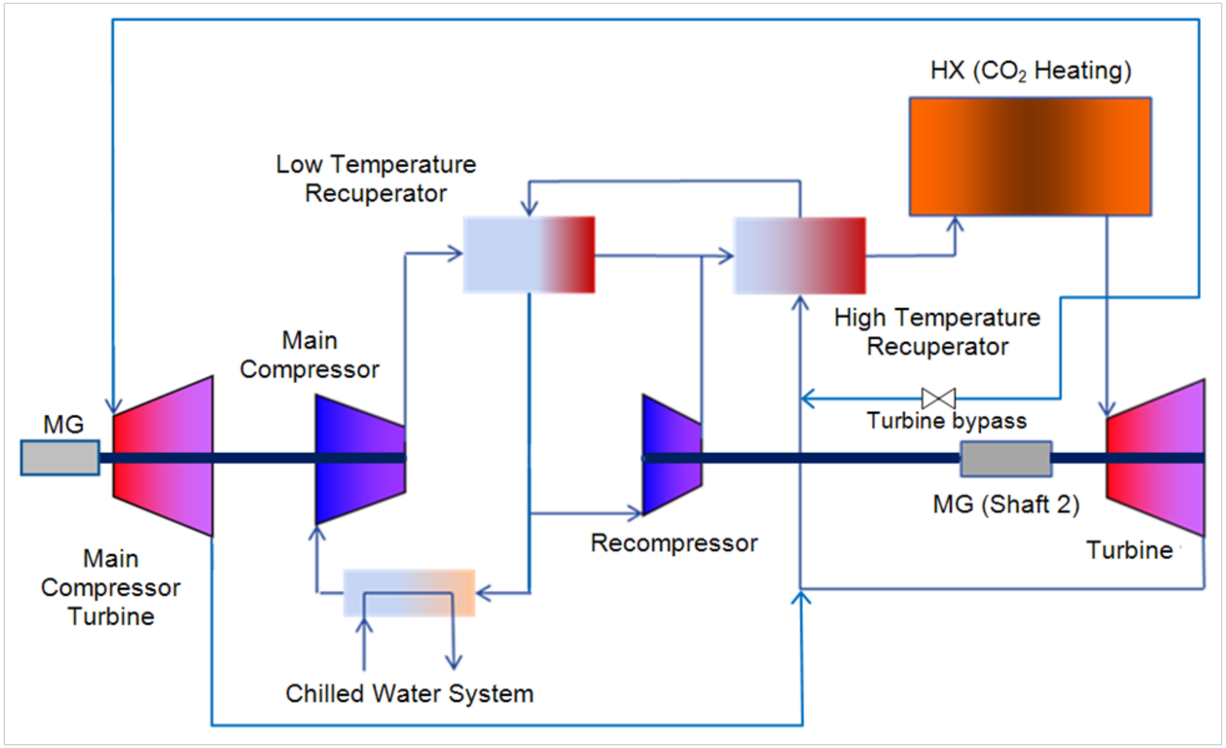




Recompression Disadvantages: Higher initial cost (more components) and more complex control of loop startup, heatup and power operations

Background: Recompression Loop

Recompression loop concepts typically do not show control features needed for all operations



Recompression Loop Design must facilitate:

- Starting and stopping both compressors, loop heatup, power maneuvers and casualties
- Avoiding compressor surge, the key to Brayton Loop operations, in ***both*** compressors

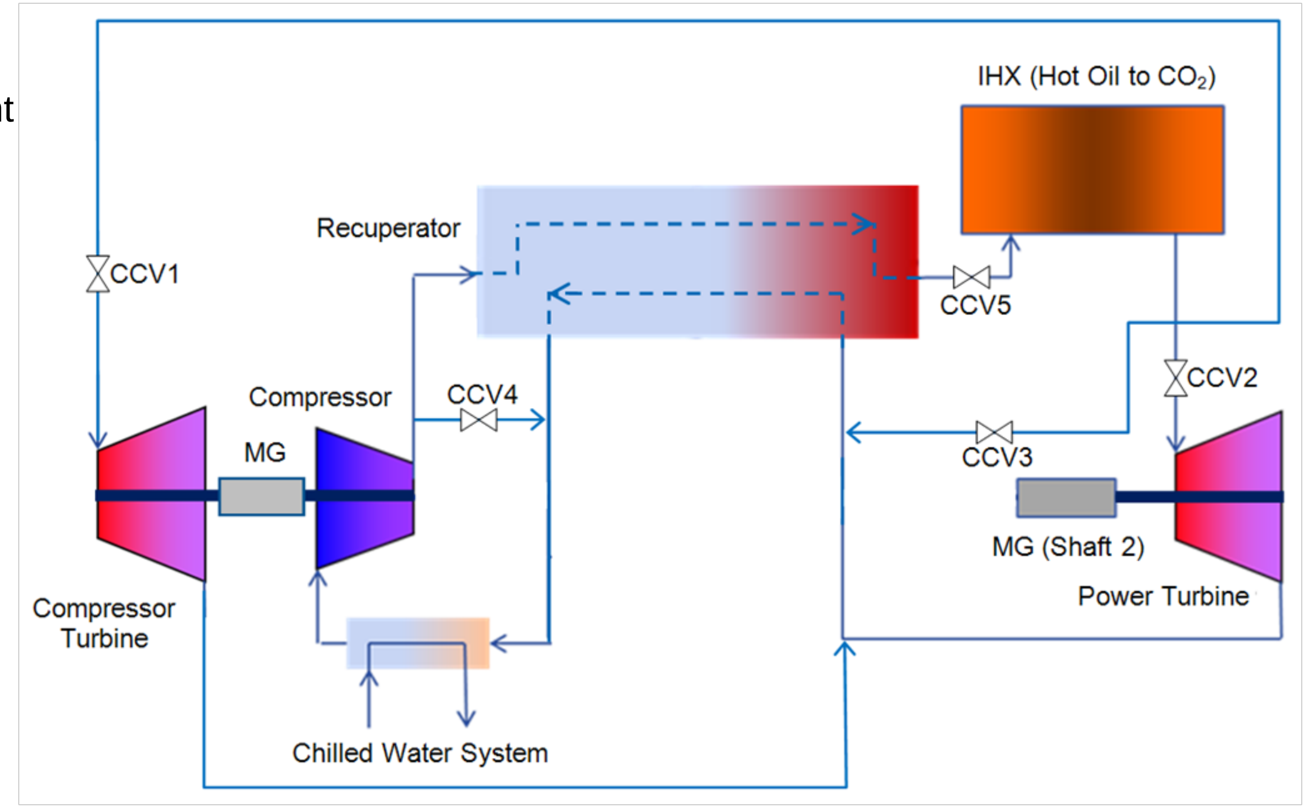
Modeling experience with the IST suggest additional control features should include:

- Isolation valves to modify loop configuration
- Compressor recirculation control (2) to modify hydraulic conditions and,
- Automatic control to maintain the correct performance balance between compressors

Background: Integrated System Test (IST)

The IST was designed for code/model validation and control testing. In order to support the full range of plant operations, the IST has numerous control features:

- S1 & S2 Speed (MG) control
- Compressor recirculation valve (CCV4)
- Turbine throttle valves (CCV1, CCV2)
- Turbine bypass valve (CCV3)
- Compressor inlet temp (CWS flow & temp)
- Turbine inlet temp (heater power)



The capabilities of all control features are simulated with the TRACE transient code.
Control strategies have been developed to perform startup, heatup and power maneuvers without causing compressor surge.

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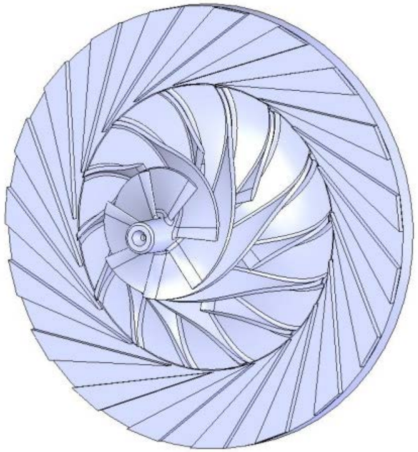
Background: Creating new recompression model

- The IST two shaft layout consists of 1) compressor-MG-turbine and 2) turbine-MG
- The IST2 recompression loop is created by attaching a recompressor to the IST TG (shaft 2)
- *Minimal* changes are made to convert the IST model to IST2 model
- An optimized design would re-size the turbines to operate at the total compressor flow (17 lbm/s)

Component and shaft number	Design inlet temp (F)	Design inlet density (lbm/ft^3)	Design flow rate (lbm/s)	Design Speed (rpm)
Compressor (shaft 1)	96	42	12.2	75,000
Recompressor (shaft 2)	140	12	5.0	75,000
Compressor Turbine (shaft 1)	570	10	5.3	75,000
Recompressor Turbine (shaft 2)	570	10	6.1	75,000

The compressor and recompressor are designed for very different fluid density, however at startup the inlet conditions may be similar.
The performance relationship between the two compressors will continually change during heatup and power changes.

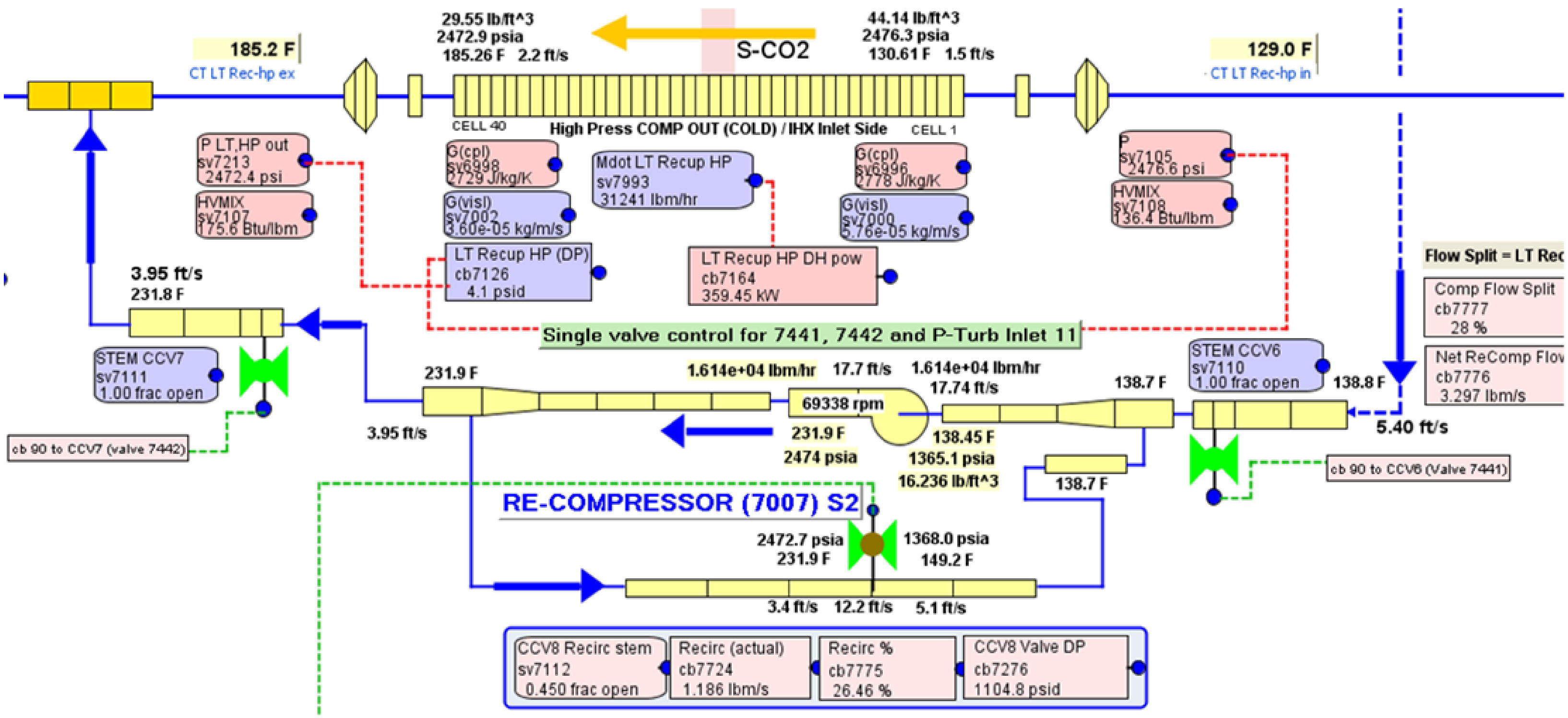
Attempting to start and run both compressors at similar inlet conditions will result in compressor surge.



Recommended Loop Design Features

The IST transient model was modified to include a second compressor and recuperator. Control features were added based on IST startup testing and modeling.

The illustration below shows control valves to isolate the recompressor (during compressor startup and initial heatup), and a recirculation control valve to adjust the system flow resistance when operating the recompressor and compressor together.



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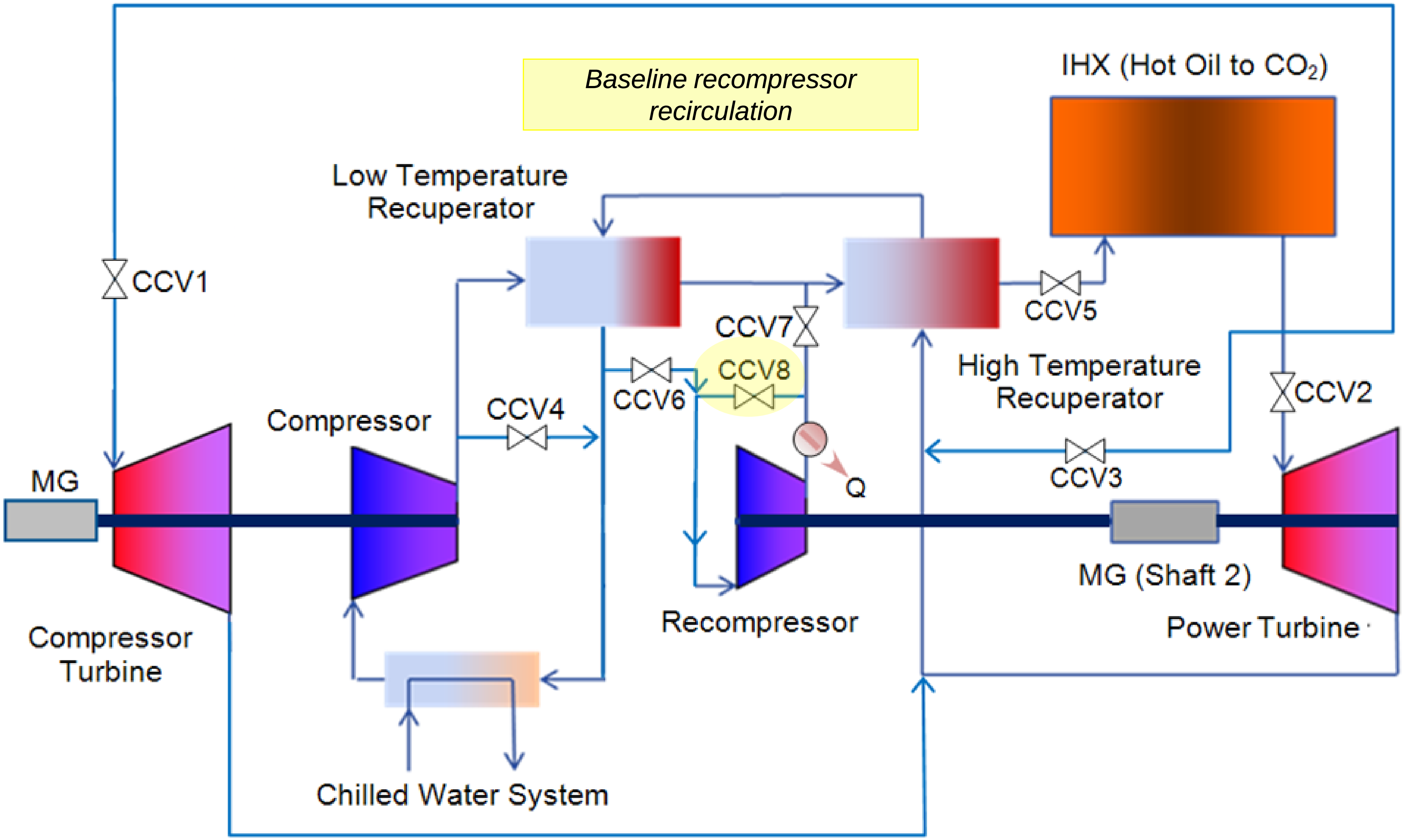
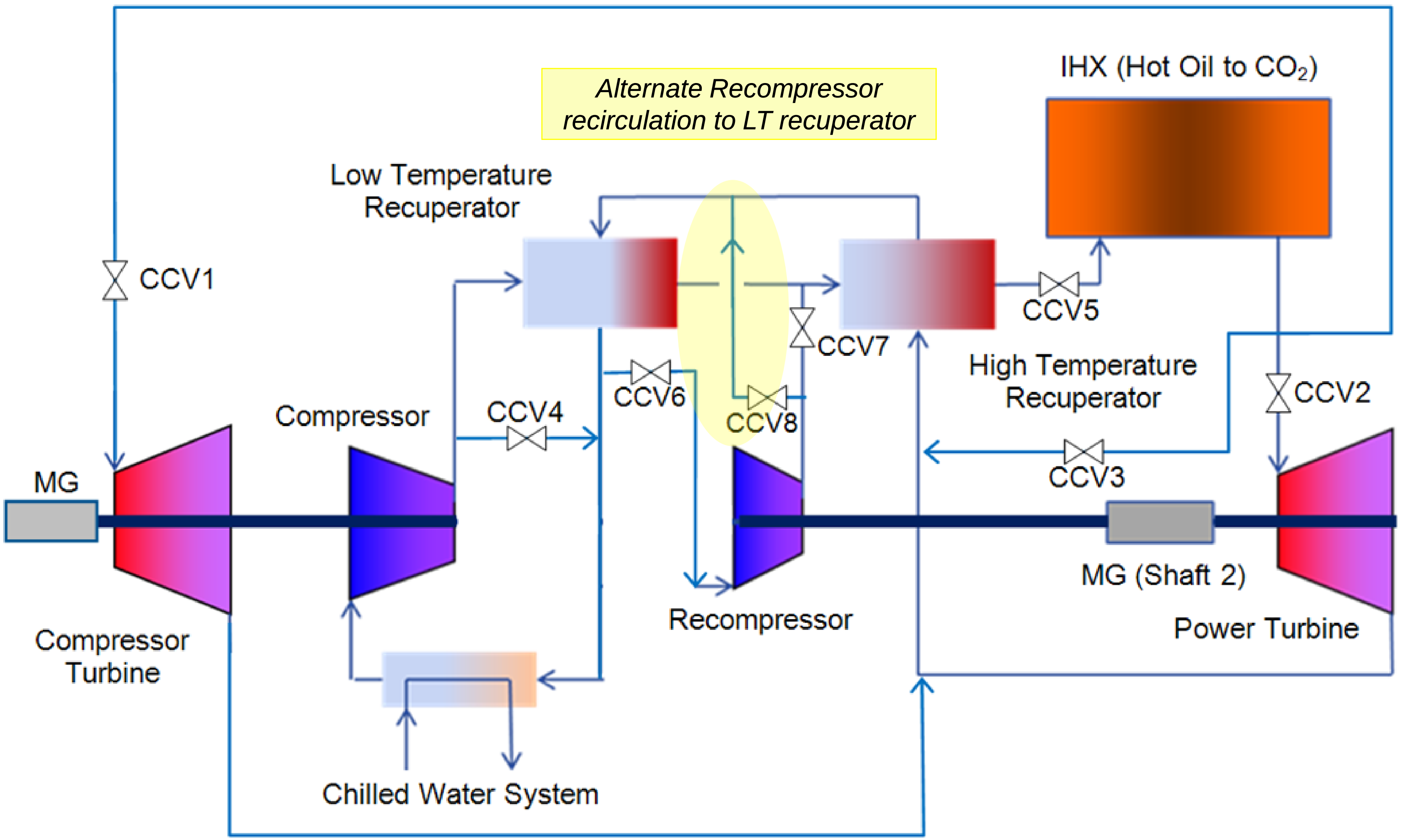
Loop with control features (baseline recirculation)



This loop design shows how control features have been placed in the IST2, allowing loop hydraulic control for startup, heatup and low power operation.

Loop & control features (recirculation to recuperator)



This loop design (IST2r) eliminates the need for a recompressor recirculation path cooler and creates different loop hydraulics for startup, heatup and low power operation.

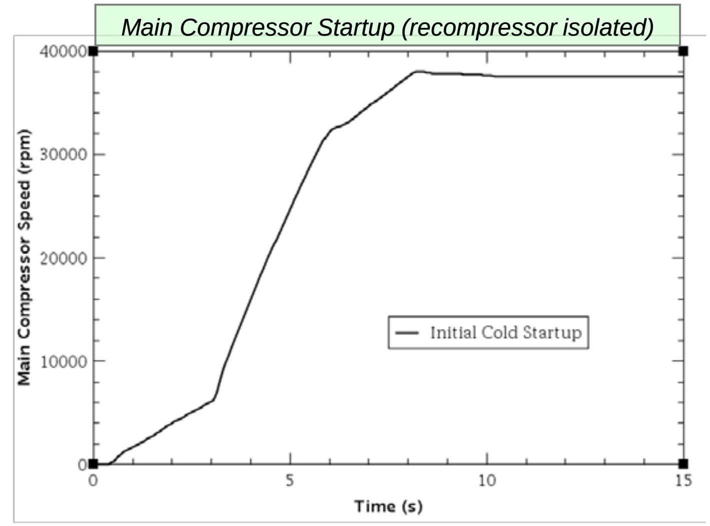
Modeling: Strategy

Modify IST TRACE model to evaluate control features and strategy needed to successfully operate S-CO_2 Brayton recompression cycle.

The following operations are considered:

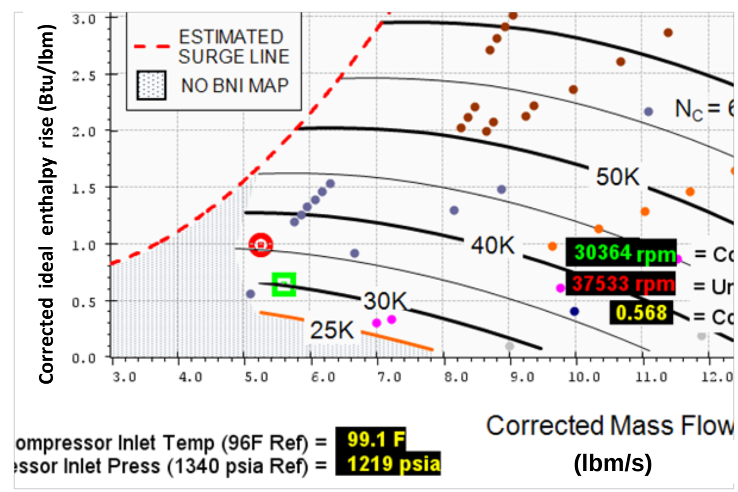
Operations (not necessarily in this order)

- Compressor startup
- Recompressor startup
- Loop heatup
- Turbine 1 startup
- Turbine 2 startup
- Power operation (variable)
- Full Power operation at maximum efficiency

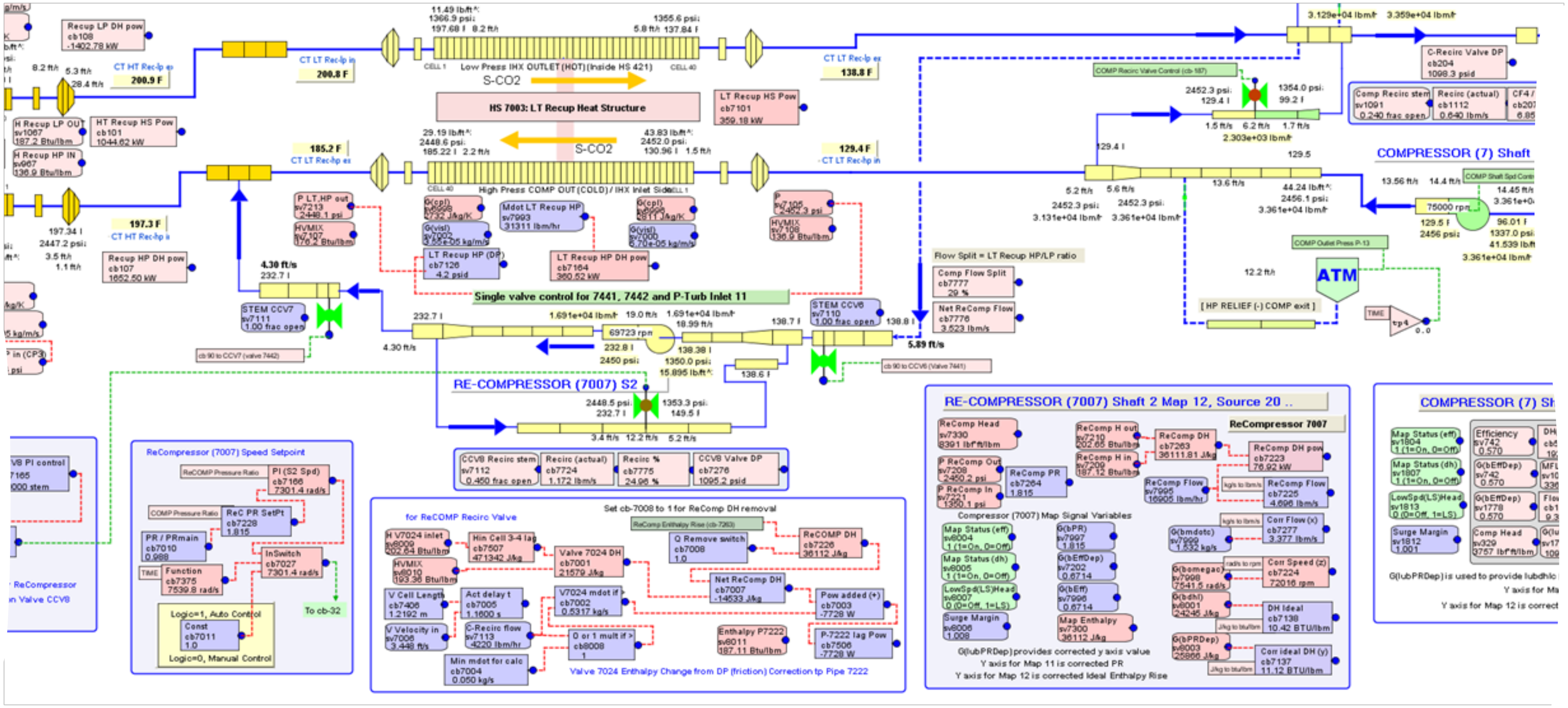


Objectives of the integrated control features will be:

- Prevent compressor and recompressor surge
- Maintain forward flow in turbines
- Maximize efficiency
- Simplify operation



Modified recompression IST2 model



Recompressor added to IST model with dedicated recirculation path (baseline IST2)

1. Building from the existing IST model greatly reduces scope of effort
2. Using available turbomachinery designs reduces scope and cost
3. The design mismatch between the IST turbo-machines and system design will extend the control challenge to all operations (including full power)

The IST model is modified to include a recompressor, a second recuperator, piping and control valves for recompressor isolation, recirculation flow control, and I&C for recompressor operation.

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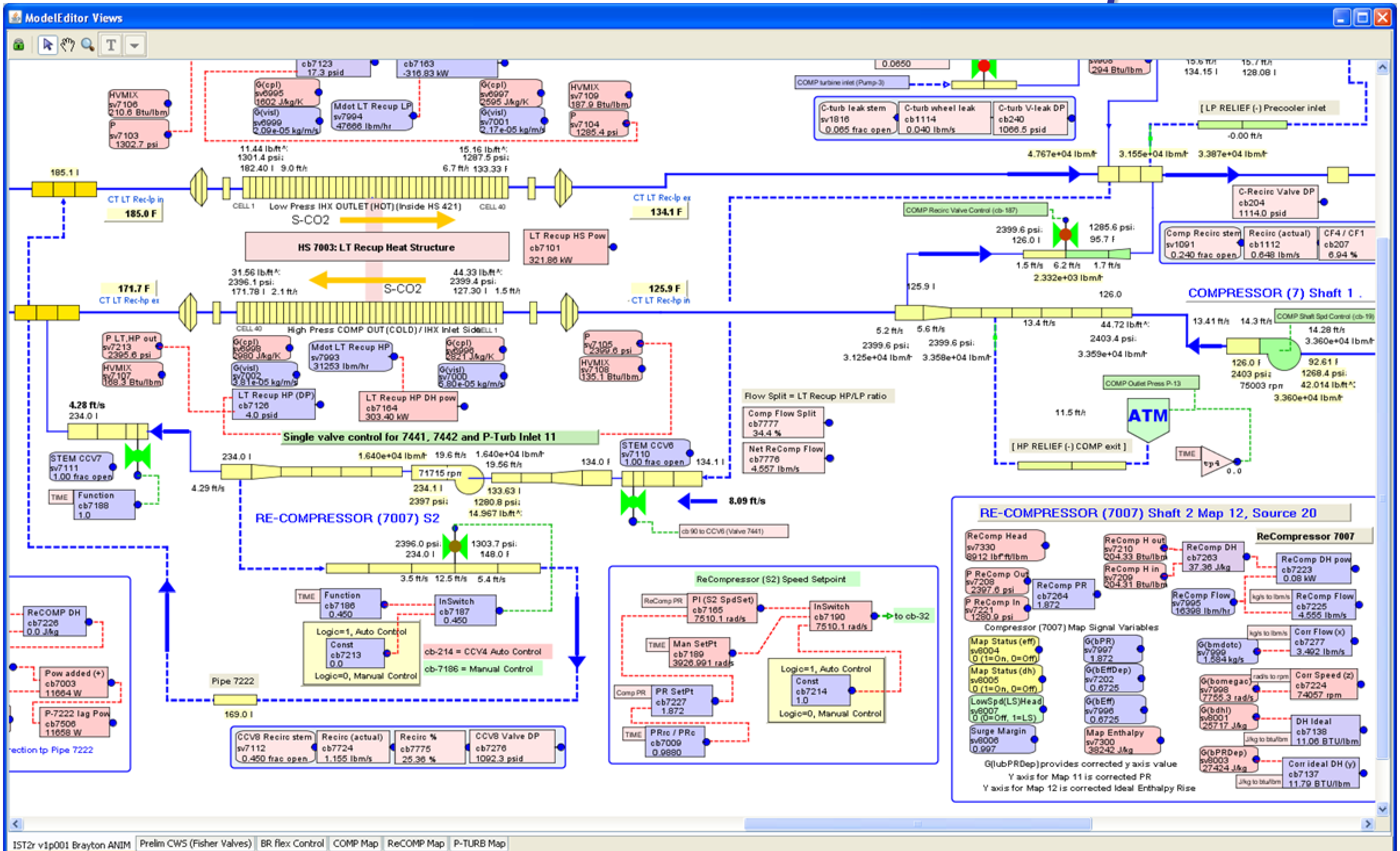
IST2r Model with alternate recirculation path



This figure represents a portion of the IST2r recompression model animation showing recompressor, low temperature recuperator, isolation valves and an alternate recirculation path

Recompressor control

The original IST has two shafts:

1) Compressor – MG – Turbine
2) Power Turbine – MG

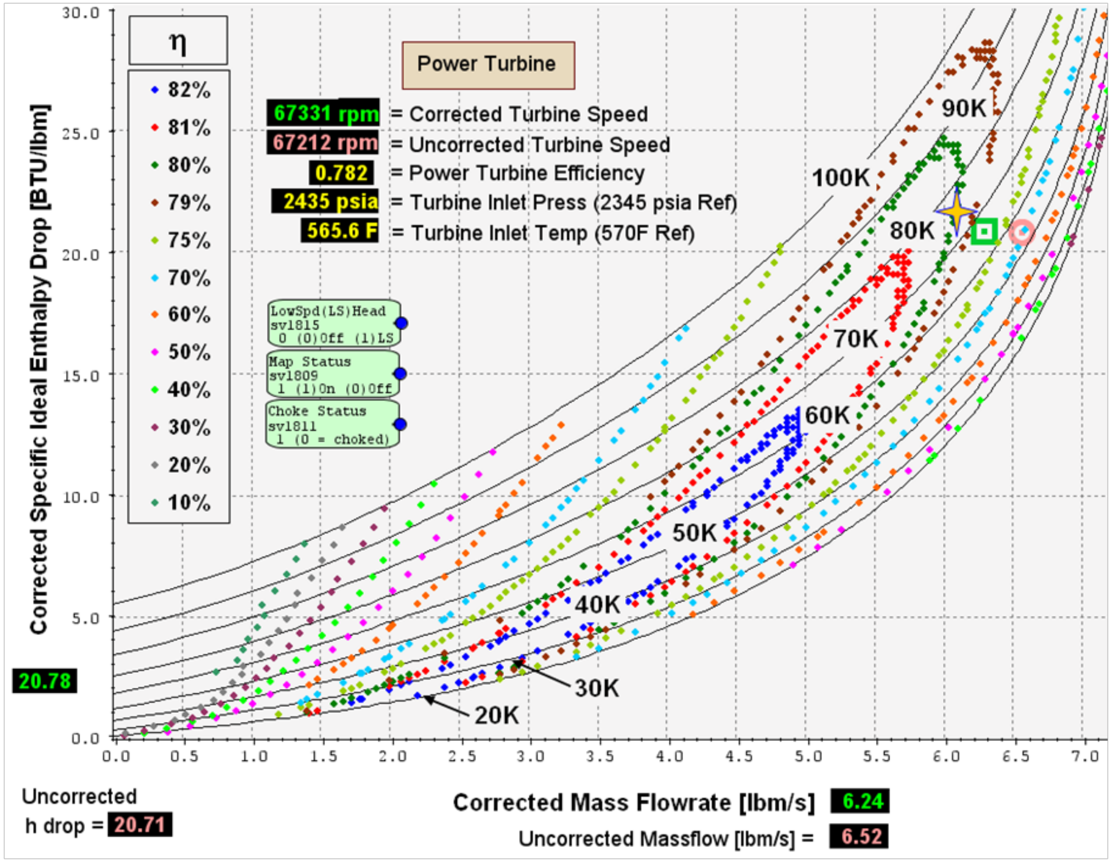
where MG = Motor/Generator

Shaft 1 was operated at variable speed and Shaft 2 at constant speed.

The *recompressor* is connected to the original IST Power Turbine and will be operated at variable speed.

Power Turbine – MG – ***Recompressor***

This recompression design will produce electric power from both shafts



The majority of the IST loop has <u>not</u> been redesigned for the recompression cycle.

In its new configuration, Brayton recompression loop efficiency and power output are reduced. Since this loop model is used for a control study these changes do not diminish its value.

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Transient Analysis – Loop Startup

Main compressor startup is performed with the recompressor at 0 rpm:

- Recompressor and power turbine isolated
- Turbine inlet at 150°F, 1250 psia
- Main Compressor inlet at 100°F, 1250 psia
- Main Compressor shaft motored to half speed

With Brayton loop flow established turbine inlet is increased to at least 300°F.

Depending on the intermediate temperature selected it may be necessary to pre-warm the power turbine before starting the recompressor.

The recompressor is started as follows:

- Recompressor and power turbine isolation valves may be "cracked open"
- Recompressor started in full recirculation (isolated from main loop or in conjunction with opening loop isolation valves)
- Prior to hydraulically coupling (opening isolation valves) the compressors, the main compressor speed is increased as necessary to balance the pressure ratio's
- The recirculation flow control valves (2) are set as needed to create an overall system flow resistance that provides adequate surge margin to both compressors

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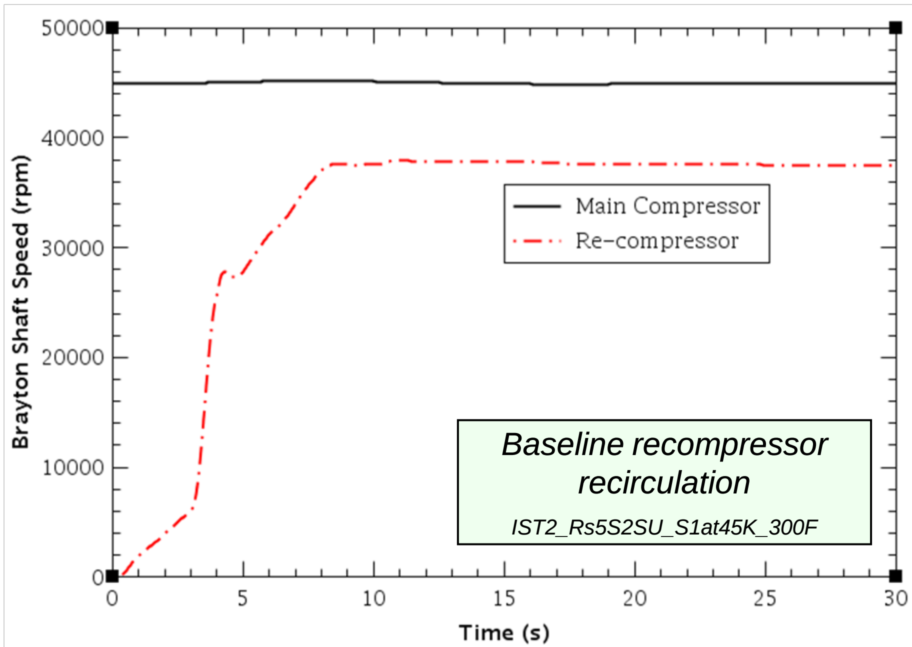
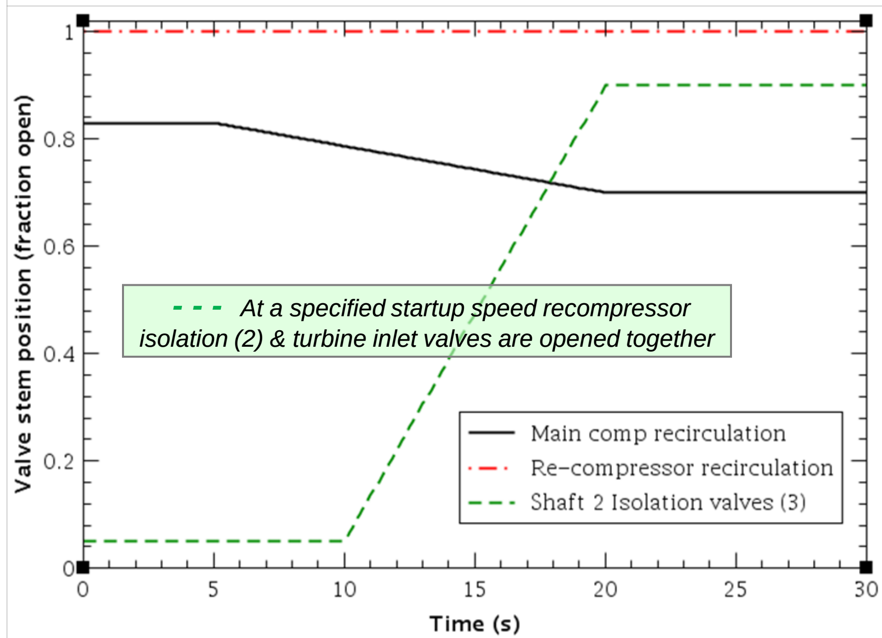
Transient Analysis - Startup

An integrated transient model is used to determine the loop hydraulic conditions that support acceptable compressor and turbine startup at very off-design conditions. Startup requires using compressor recirculation flow paths and control valves.

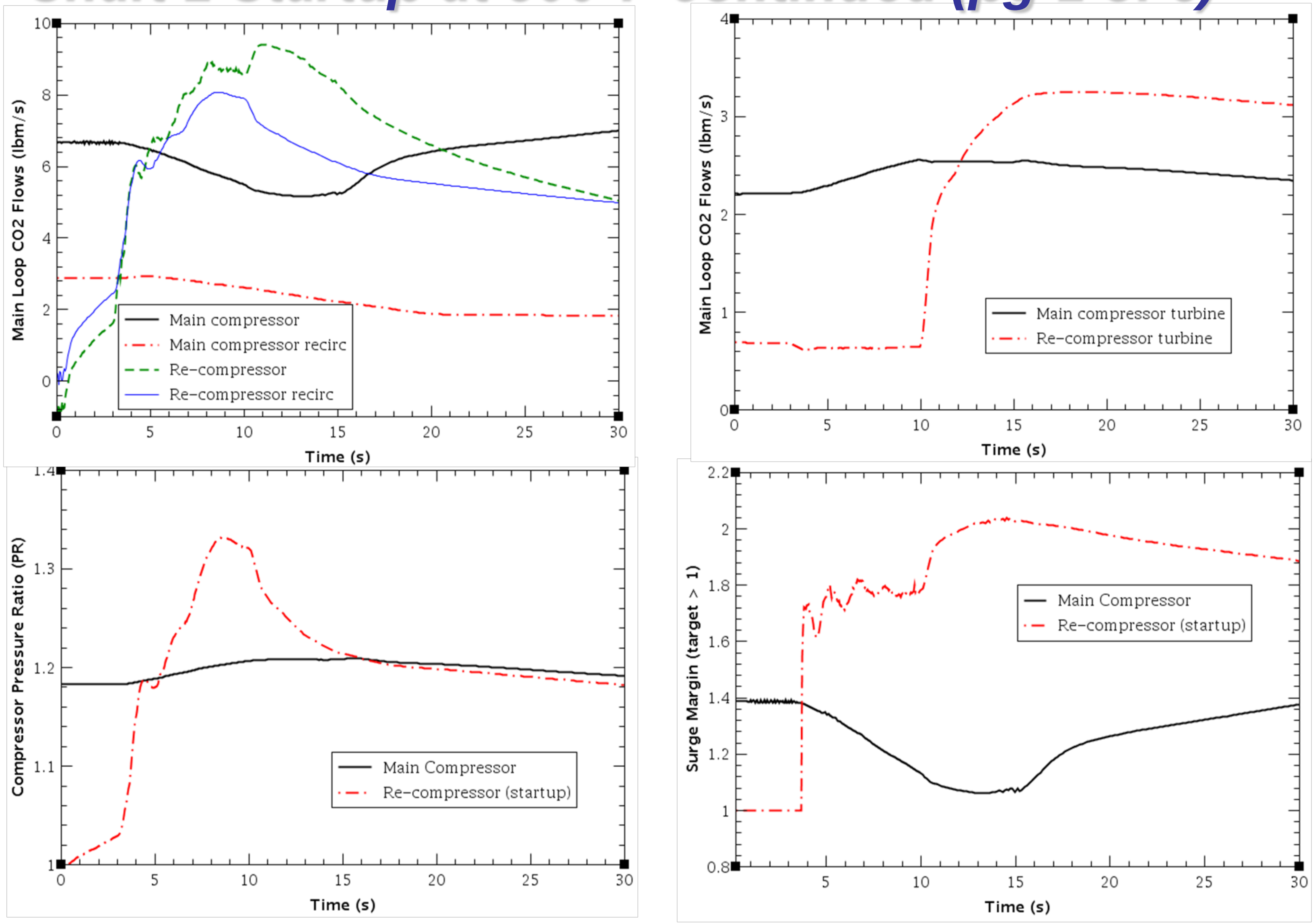
The turbine bypass should remain shut to prevent turbine flow reversal.





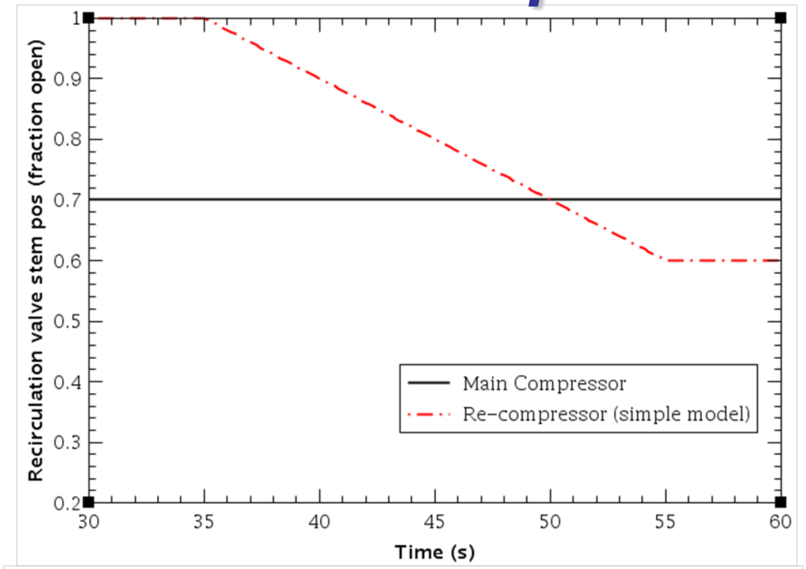
Recompressor (Shaft 2) startup at 300°F is accomplished with recirculation for both compressors. After the startup transient the recompressor and power turbine isolation valves (3) are opened to reach the normal flow configuration.

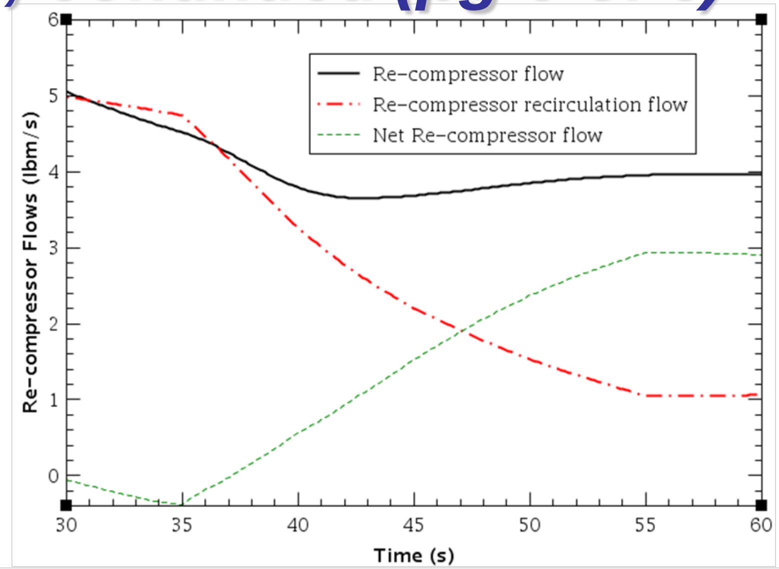
Shaft 2 Startup at 300°F continued (pg 2 of 3)

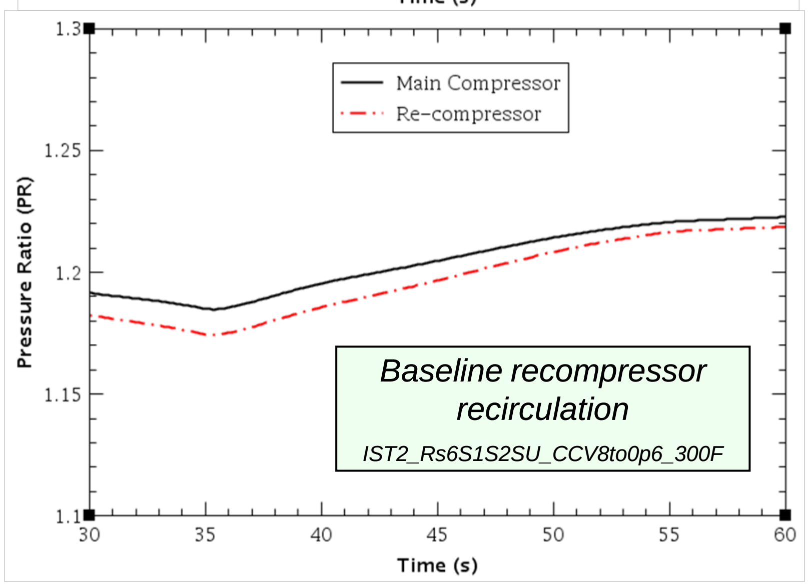


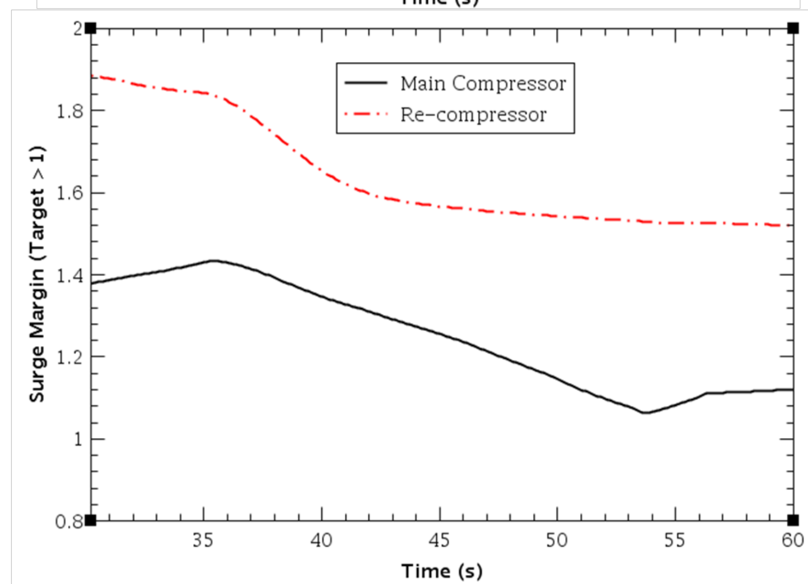
Recompressor (Shaft 2) startup, initially with all flow recirculated (0 to 10 sec).

Shaft 2 Startup at 300°F, continued (pg 3 of 3)









Transient produced by throttling the recompressor recirculation valve (only action)

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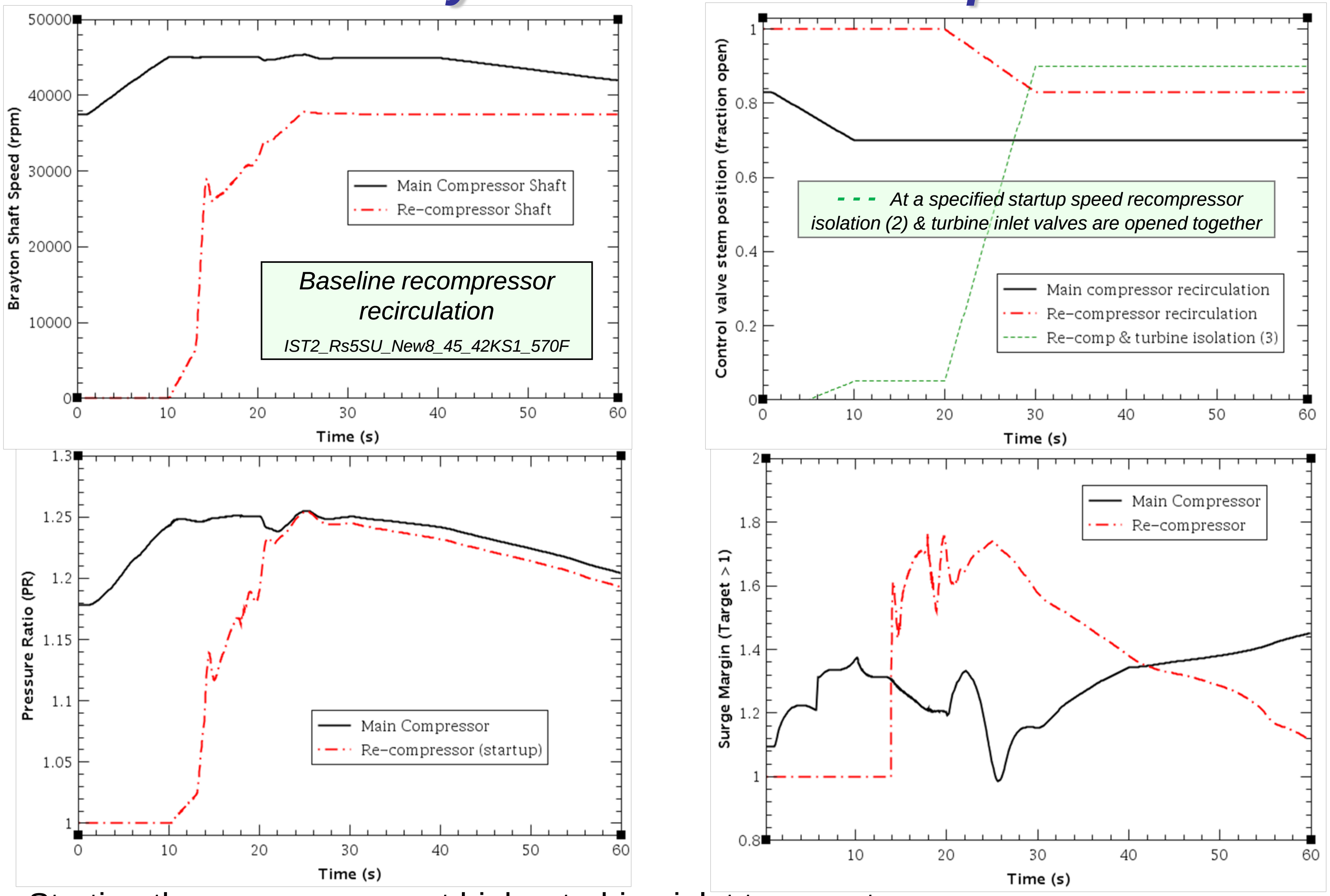
Transient Analysis – Shaft 2 Startup at 570°F



Starting the recompressor at higher turbine inlet temperature

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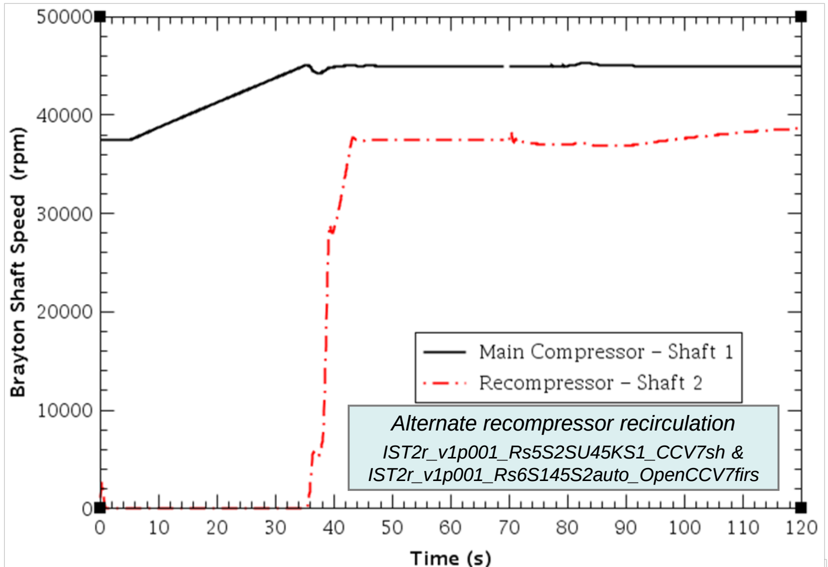
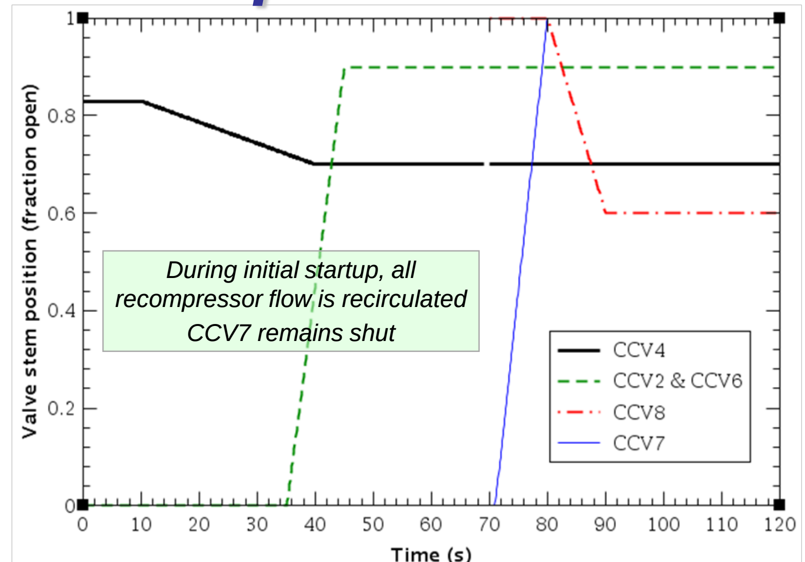
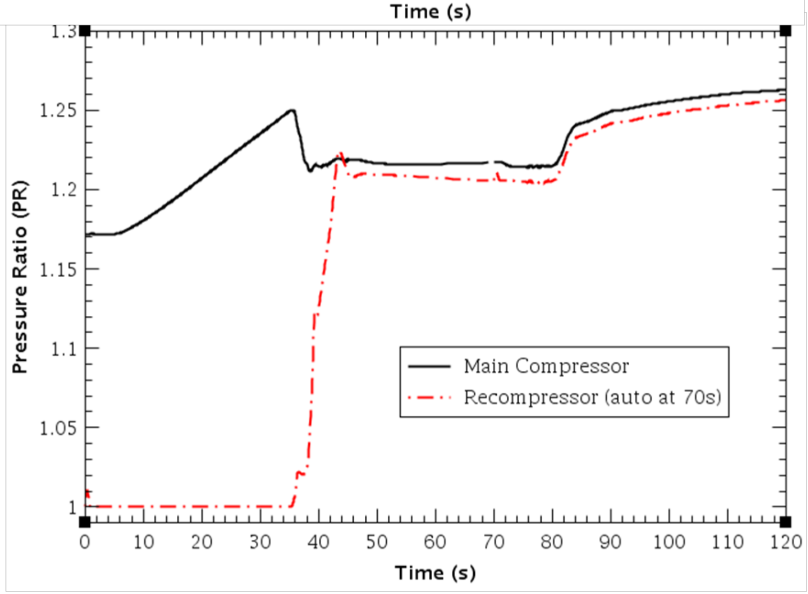
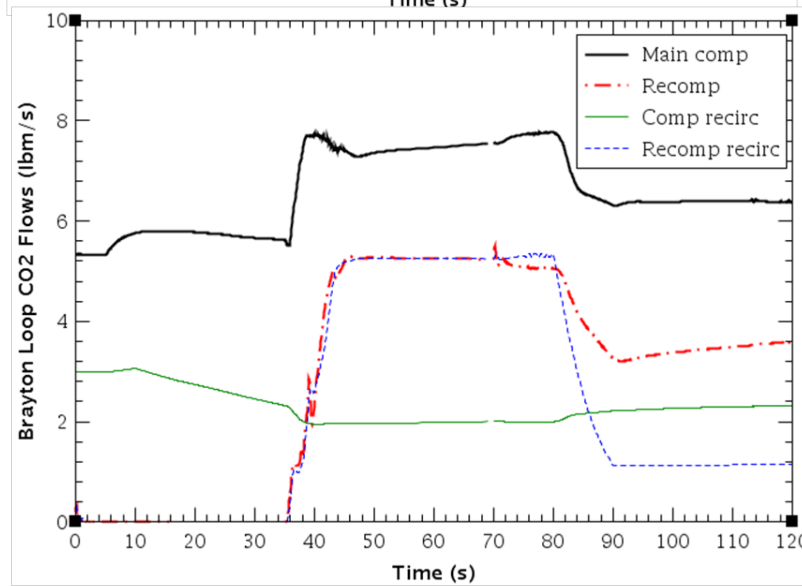
IST2r Model – Shaft 2 Startup at 400°F



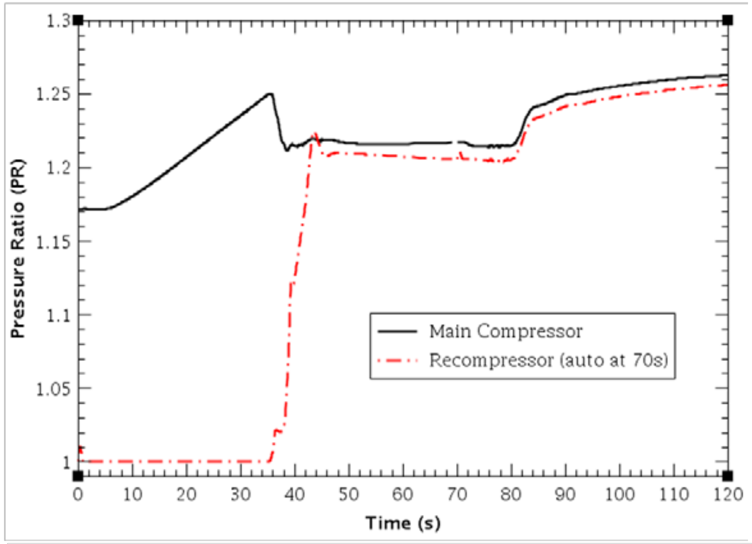






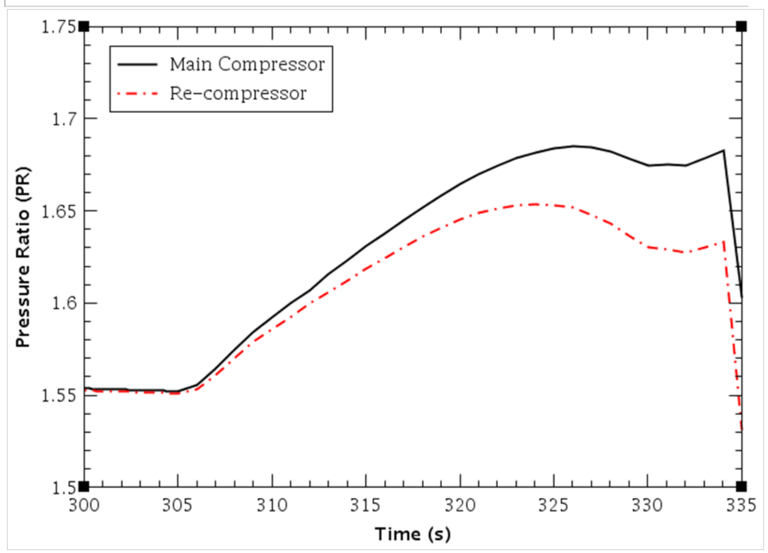
Recompressor (Shaft 2) startup using *alternate recompressor recirculation path.*

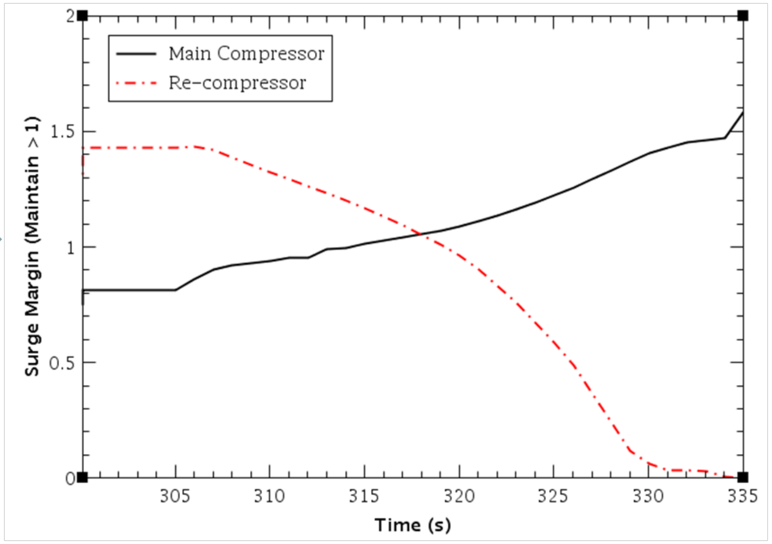
Automatic Recompressor Control



On the previous slide automatic recompressor control was initiated at 70 seconds. The result was that as CCV8 was throttled to reduce recirculation flow and the main compressor Pressure Ratio (PR) increased, the recirculation PR followed closely.

The plots below show what happens if the main compressor and recompressor PR diverges.





Small differences between compressor pressure ratio (PR) may produce compressor surge. An automatic control system is needed to balance compressor performance.

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Transient Analysis – Control System Options

Balancing compressor performance is best achieved with pressure ratio (PR).

The term Pressure Ratio-Ratio (PRR) is defined as: $PR_{recompressor} / PR_{compressor}$

Two methods of maintaining the desired PRR were investigated.

1) Hydraulic Control

In a single compressor system, recirculation valve control is effective for preventing surge. However, recompression loop simulations using recirculation flow feedback control valves was unstable and not effective in maintaining the desired PRR.

- Control using compressor and recompressor recirculation valves affected surge margin but did not allow the performance balance between compressors (PRR) to be adjusted.
- Feedback control stability was also an issue (illustration on the following slide)

2) Recompressor Speed Setpoint Control

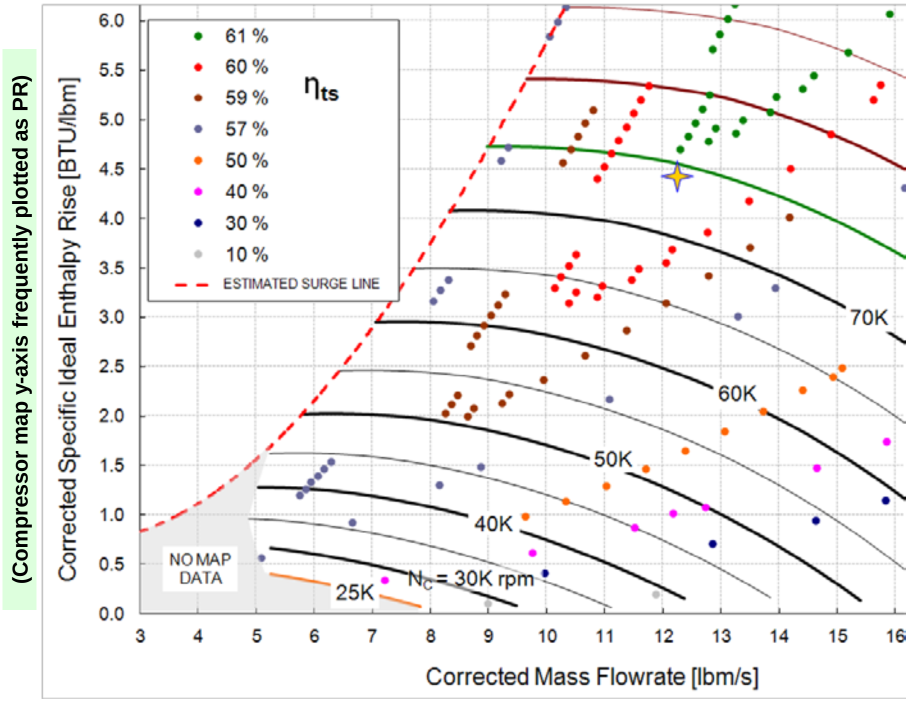
Recompressor speed change is much more effective in changing PR.

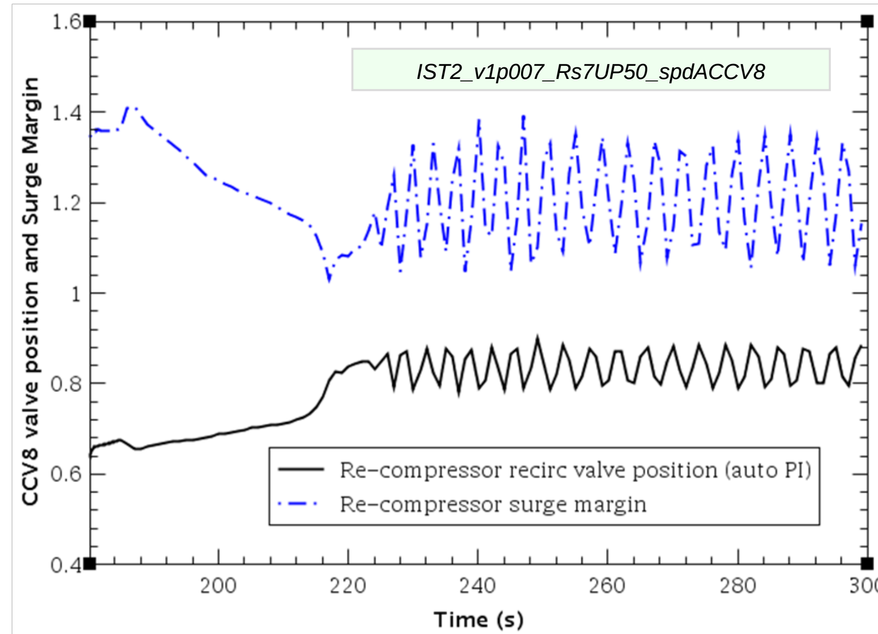
Near the surge line, speed is directly proportional to enthalpy rise (and PR), resulting in stable feedback control

Transient Analysis – Pressure Ratio (PRR) control

For S-CO_2 analysis ΔH ideal has been used (see map below).

However, PR is still directly related to ΔH (y-axis).





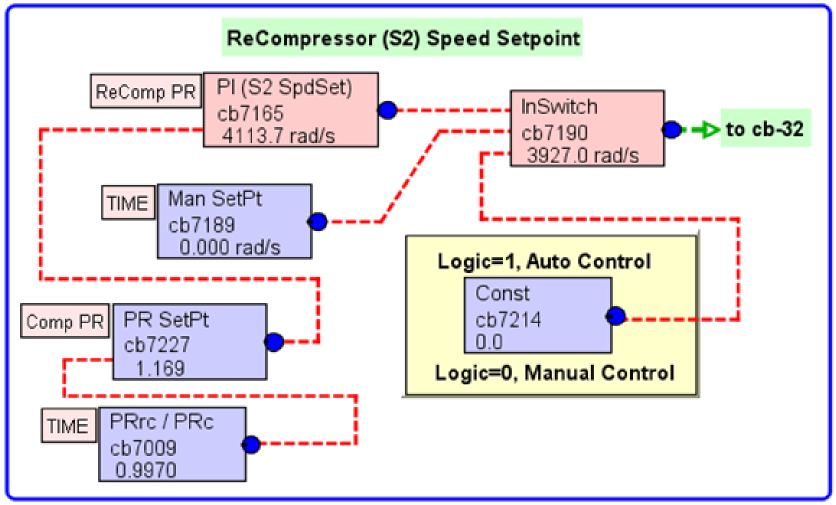
1) <u>*Hydraulic Control (CCV8)*</u>

Using loop hydraulics to control PR has poor stability (right plot). This is due to the nearly flat shape of constant speed lines as surge is approached.

2) <u>*Recompressor Speed Setpoint Control*</u>

Near the surge line (see map), speed is directly proportional to enthalpy rise (and PR).

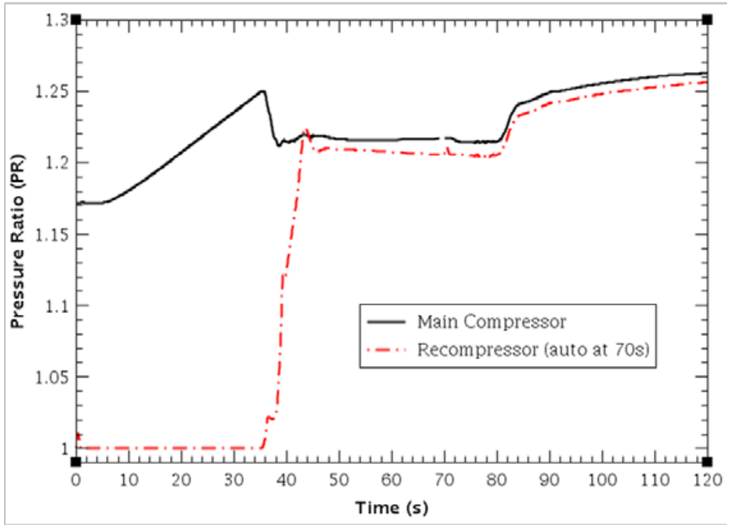
Transient Analysis – Using PR control

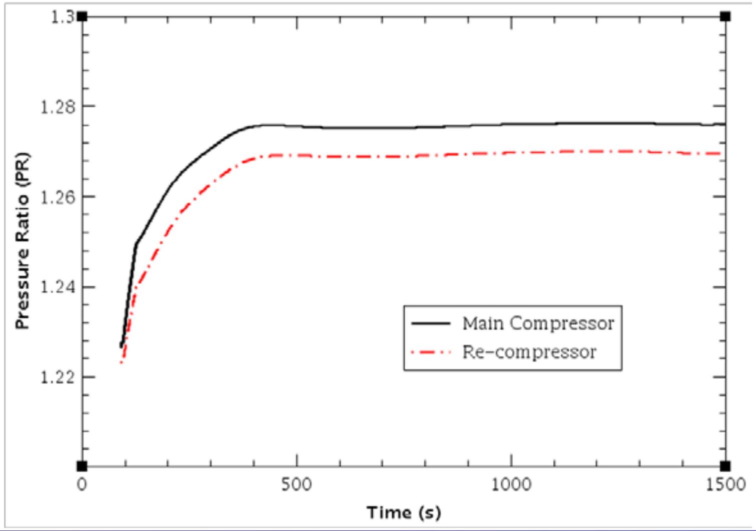


Automatic control multiplies (cb7227) the measured main compressor PR by the PRR setpoint (cb7009) to define the desired recompressor PR. A feedback PI controller (cb7165) then dynamically adjusts the recompressor speed *setpoint* until the measured recompressor PR matches the required value.

Another controller (not shown) adjusts the power or load to the Shaft 2 motor generator match recompressor speed with its *setpoint*.

The plots below show the effectiveness of PRR control when changing loop valve positions or making compressor speed changes. The controller works for fast and slow transients





Transient Analysis – Optimized high power HB

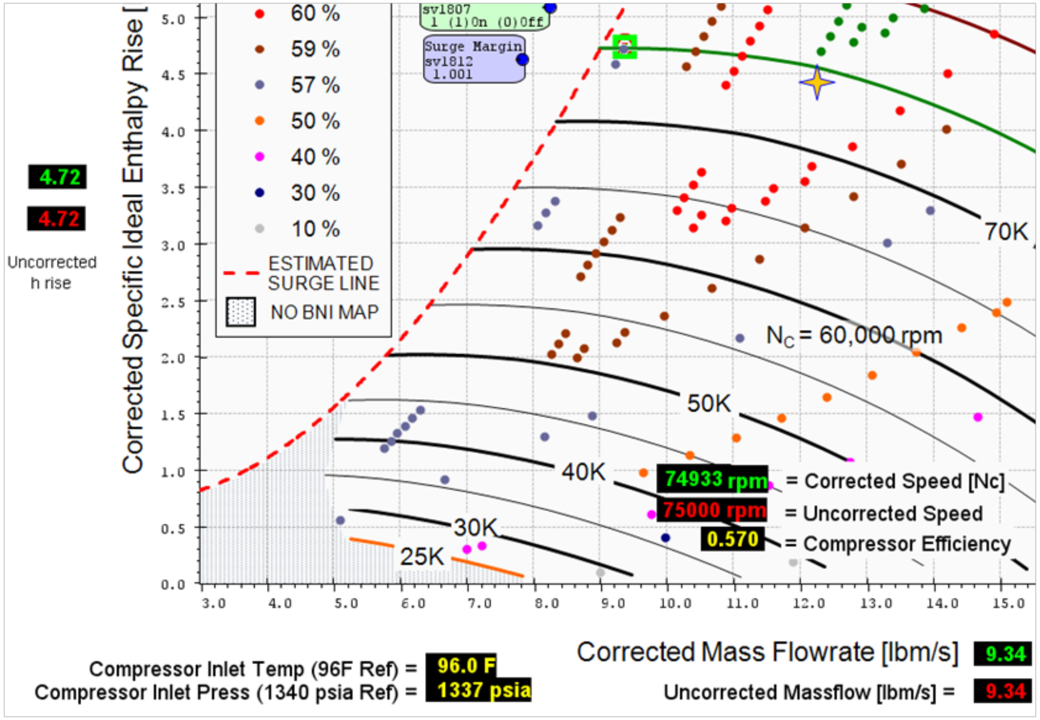
PRR control is used to find the optimized maximum power heat balance. Since maximum power output is at minimum surge margin, the PRR setpoint and recirculation valve positions are adjusted for a surge margin of 1.0.

At an IST2 surge margin of 1.0:

PRR setpoint = 0.988

Compressor = 75,000 rpm 9.3 lbm/s, PR = 1.84

Recompressor = 69,723 rpm 4.7 lbm/s & PR of 1.82



The compressor operating conditions above are produced by using a main compressor recirculation valve setpoint of 24% and recompressor recirculation valve setpoint of 45%. The PRR ($PR_{R\text{-}C}/PR_C$ Ratio) is 0.988 resulting in a compressor flow split of 29% (net recompressor flow / total flow) and producing 50.5 kW.

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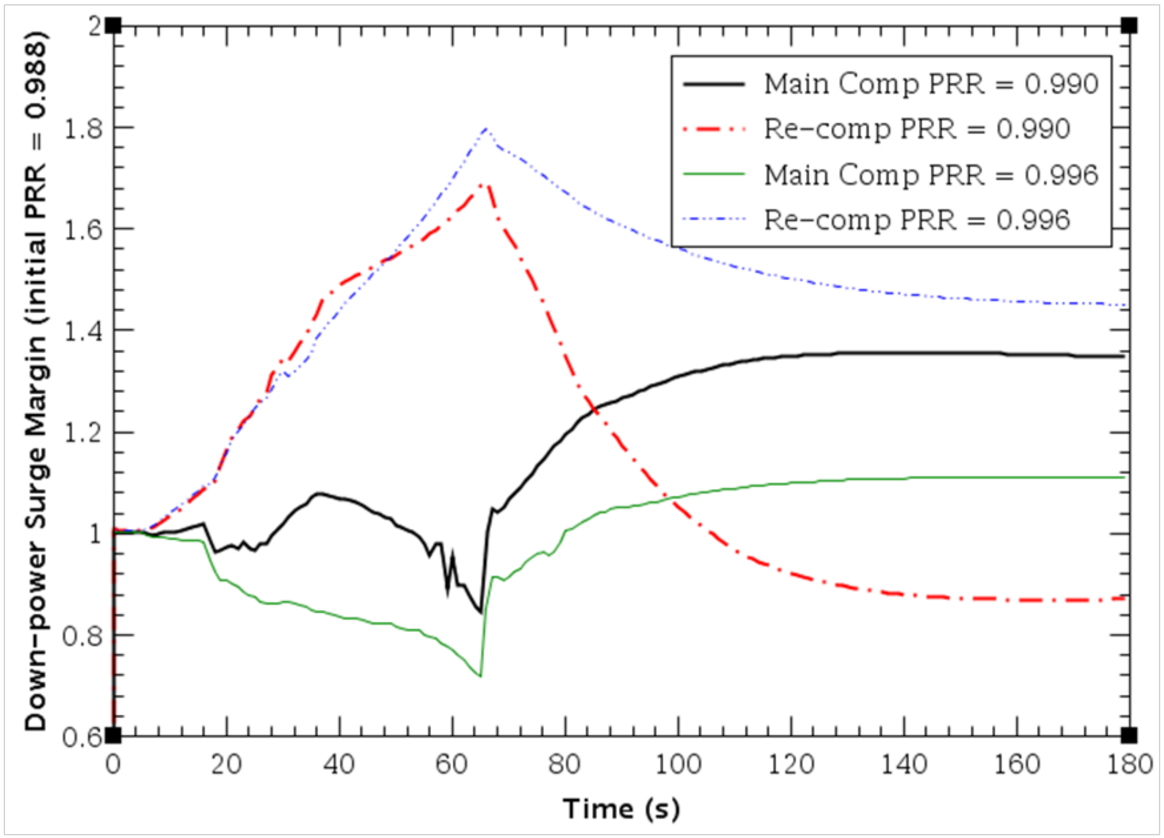
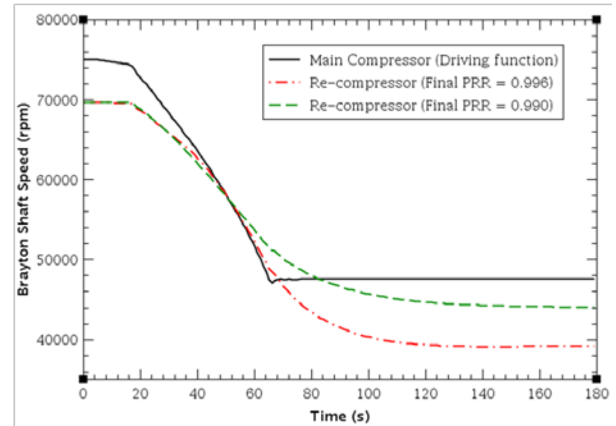
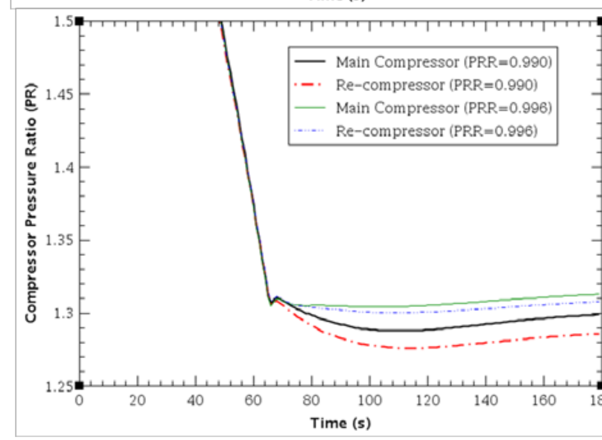
Transient Analysis – Optimized low power

Reducing power from the optimized full power condition requires slight adjustments to the PR_{R-C}/PR_C ratio (PRR). Surge margin is very sensitive to the performance balance.







At a low power S1 speed of 47,630 rpm (~10% power) a decrease in PRR from 0.996 to 0.990 reduces the recompressor surge margin by a huge amount from 1.45 to 0.87. The optimum PRR is between these values and moves comp and re-comp SM closer.

Down-power Maneuver (IST2)

Baseline recompressor recirculation

IST2_v1p007_Rs11DP10p_PRRgain5E4

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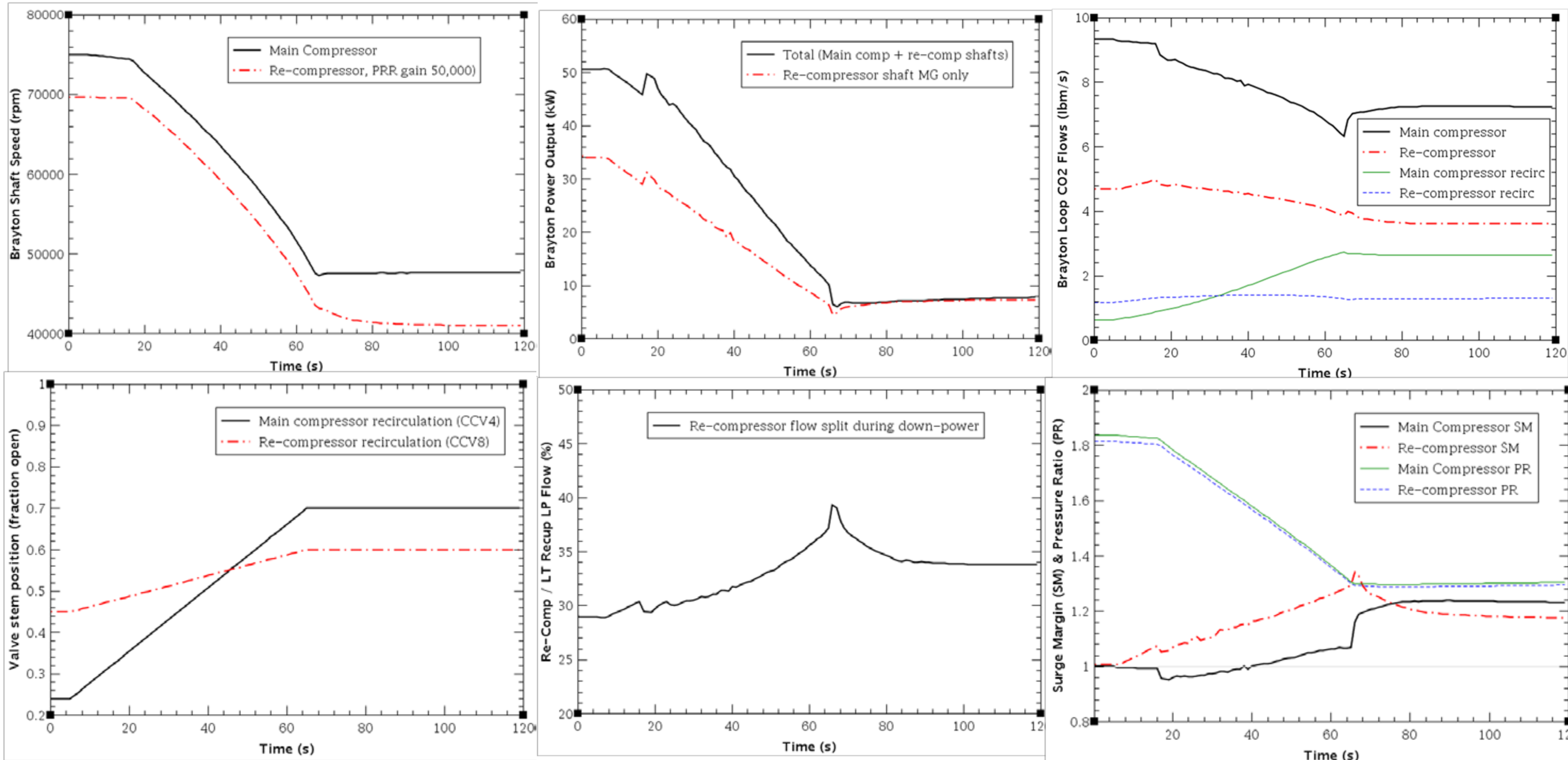
End states have been optimized for adequate surge margin, but rapid down-powers will transiently move compressor operation in the direction of surge



With limited surge margin at high power, rapid IST2 down-power could produce *main compressor* surge. A well designed system will have greater surge margin.

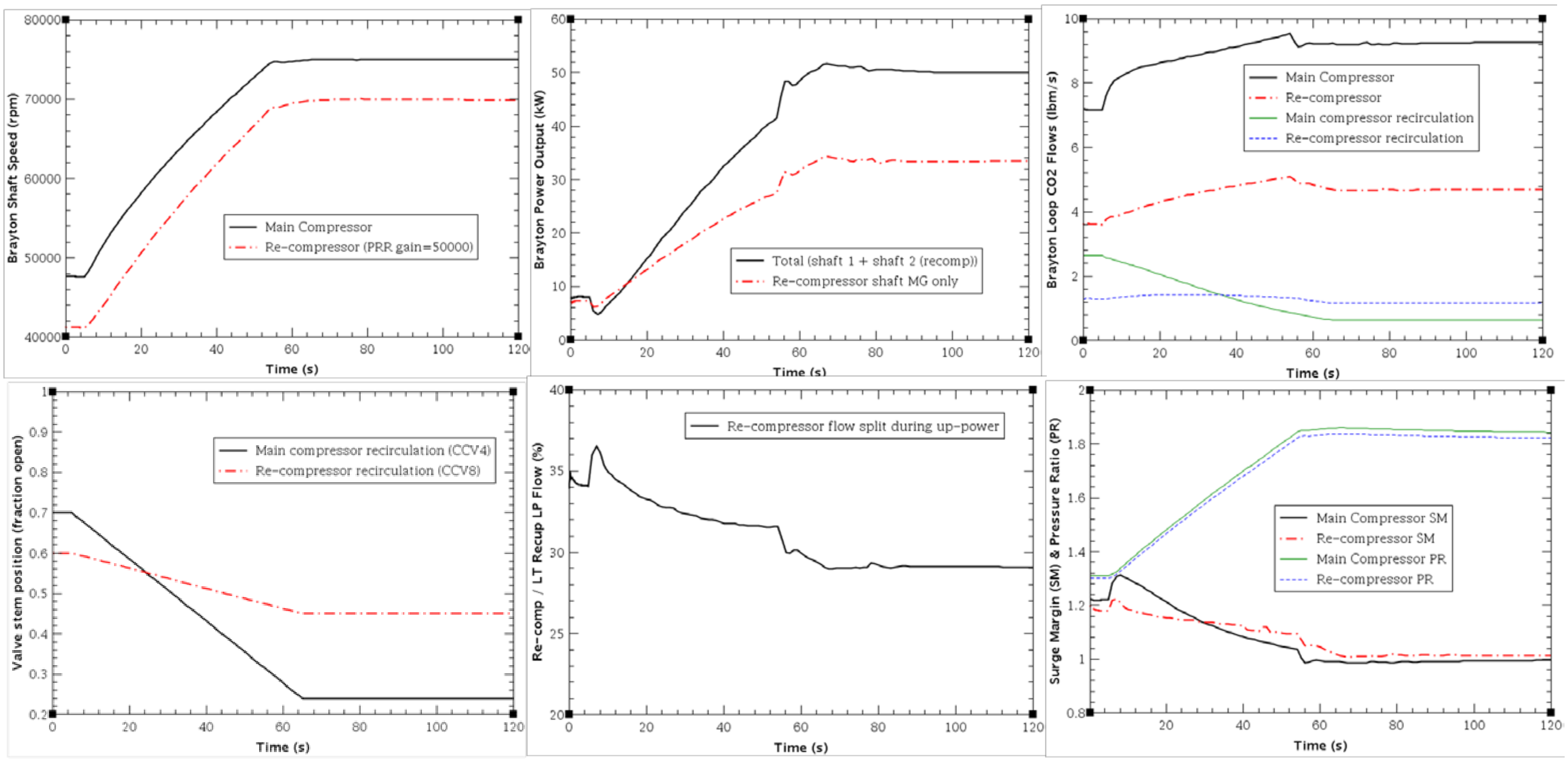
➢ *IST2r downpower results were similar to the IST2 model.*

Up-power Maneuver (IST2)

Baseline recompressor recirculation

IST2_v4p013_Rs12UP75K_PRRp988_mH

Using end states that have been optimized for adequate surge margin this up-power transient shows good performance, with minimal under/over shoot.



Up-power rates >1%/s would be possible for a well designed recompression loop.

- *IST2r downpower results were similar to the IST2 model.*

Conclusion

By starting and maneuvering an IST based Recompression loop this analysis identifies design and control features that should be applied to any recompression loop for successful operation. When system design is significantly different than analyzed here, the same basic control principles should be applied.

By demonstrating control of a Recompression loop with mismatched turbomachinery, this study provides a conservative definition of control features and methods. A conservative approach is needed to create a robust loop that can be operated at off-design conditions. Even full power operation may become "off-design" if component and system performance does not match original design specification, or degrades over time.