Recent Developments in $S\text{-}CO_2$ Cycle Dynamic Modeling and Analysis at ANL

Anton Moisseytsev and Jim Sienicki

Argonne National Laboratory, USA

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Contents

- The presentation provides an update on recent analyses of the S-CO_2 Brayton cycle at ANL
  - Since the last S-CO_2 Symposium in 2011
  - The majority of the results has been already presented at various conferences
- The analysis presented is this paper has been carried out using the Plant Dynamics Code (PDC) developed at ANL
  - Most of the S-CO_2 cycle control analysis carried out at ANL and presented here has been done in application of the cycle as an energy converter for Sodium-Cooled Fast Reactors (SFRs)
- Recent Progress
  - Coupling of the PDC with the SAS4A/SASSYS-1 code
  - Dynamic simulation and control of the S-CO_2 cycle
  - S-CO_2 cycle control with active reactor control
  - ANL Plant Dynamics Code validation

ANL Plant Dynamics Code (PDC)

- Specifically developed for analysis of S-CO_2 cycle
  - One-dimensional system level transient analysis code
  - Targets the specific features of the cycle
    - Operation close to the critical point
    - Recompression cycle (if needed)
  - Real CO_2 properties
    - Properties variation in HX's and turbomachinery
    - No ideal gas assumptions
    - Compressibility effects
- Incorporates S-CO_2 cycle control mechanisms and logic
- Incorporates steady-state design code to determine cycle initial conditions
- Integrated "semi-automatic" turbomachinery design
  - Design and performance subroutines for both turbine and compressor
- Fast solution scheme runs efficiently on a PC
  - Taylor series
  - Almost real time (for slow transients)

Coupling of the PDC with the SAS4A/SASSYS-1 Code

SAS4A/SASSYS-1 Code

- Developed by Argonne National Laboratory
- Leading capability for analysis of liquid-metal-cooled reactors at system level
  - Primary use: safety analysis
- Incorporates detailed reactor as well as primary and intermediate loop thermal hydraulics
  - Forced and natural circulation, pump models, heat exchangers
- Reactivity coefficients specific to fast reactors
  - Core axial and radial expansions, control rod expansion, coolant density, etc.
  - Radial-, axial-, and temperature-dependent distributions in transients
- Includes balance-of-plant model
  - Currently limited to steam cycles

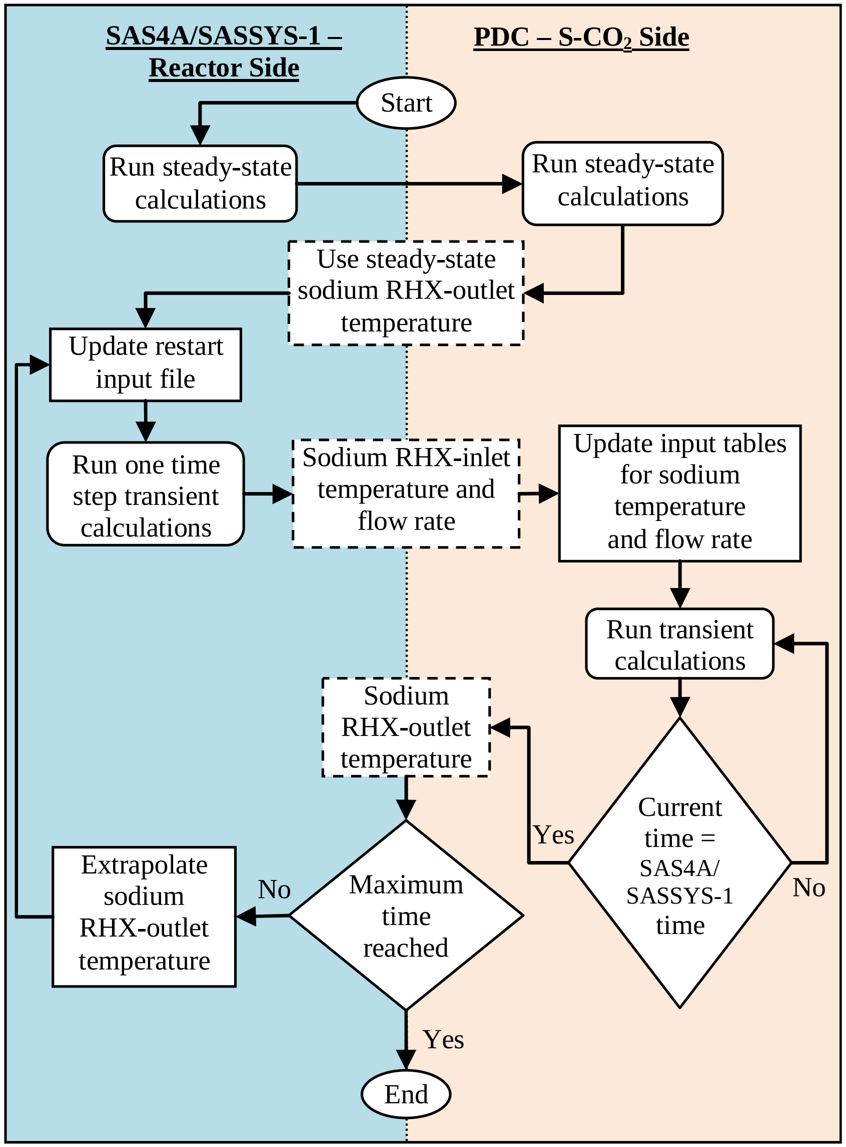
- Coupling PDC with SAS4A/SASSYS-1 would combine analysis capabilities for the reactor and S-CO_2 BOP
  - Covering the entire plant

Coupling PDC with SAS4A/SASSYS-1 code

- Coupling PDC with SAS4A/SASSYS-1 would combine analysis capabilities for the reactor and S-CO_2 BOP
  - Covering the entire plant
- However, the access to SAS4A/SASSYS-1 source code is restricted (Export Controlled)
  - Previously, the two codes were run separately with iterative update of input files
- New coupling scheme uses SAS4A/SASSYS-1 PC executable file
  - Does not require access to the SAS4A/SASSYS-1 source code
  - Utilizes Fortran capabilities to work with EXE files
  - Takes advantage of SAS4A/SASSYS-1 restart capability
- The data transfer between PDC and SAS4A/SASSYS-1
  - Occurs at each SAS4A/SASSYS-1 time step
  - Is done by reading SAS4A/SASSYS-1 output files and writing input files
  - Involves intermediate sodium conditions at RHX inlet and outlet

PDC-SAS4A/SASSYS-1 Coupling

- New coupling scheme uses SAS4A/SASSYS-1 PC executable file
  - Does not require access to the SAS4A/SASSYS-1 source code
  - Utilizes Fortran capabilities to work with EXE files
  - Takes advantage of SAS4A/SASSYS-1 restart capability
  - Could be applied to other heat source codes
- The data transfer between PDC and SAS4A/SASSYS-1
  - Occurs at each SAS4A/SASSYS-1 time step
  - Is done by reading SAS4A/SASSYS-1 output files and writing input files
  - Involves intermediate sodium conditions at RHX inlet and outlet



Dynamic Simulation and Control of the S-CO_2 Cycle

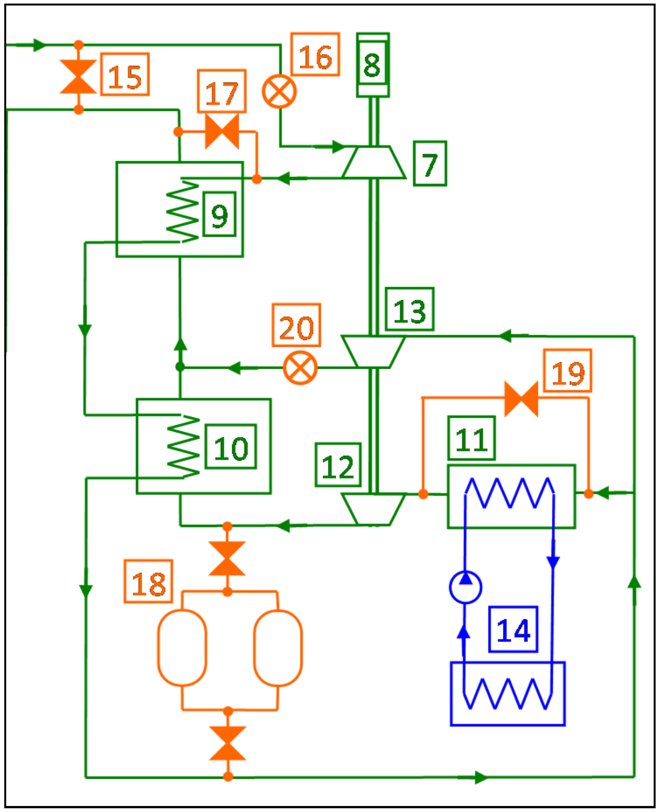
S-CO_2 Cycle Control Analyses

- Load Following
  - Goal: to show that the cycle can be controlled to change power level
  - Investigate and optimize control mechanisms

- Decay heat removal
  - Goal: demonstrate that the cycle can be used in low power regime
  - Investigate and optimize control mechanisms

S-CO_2 Cycle Control

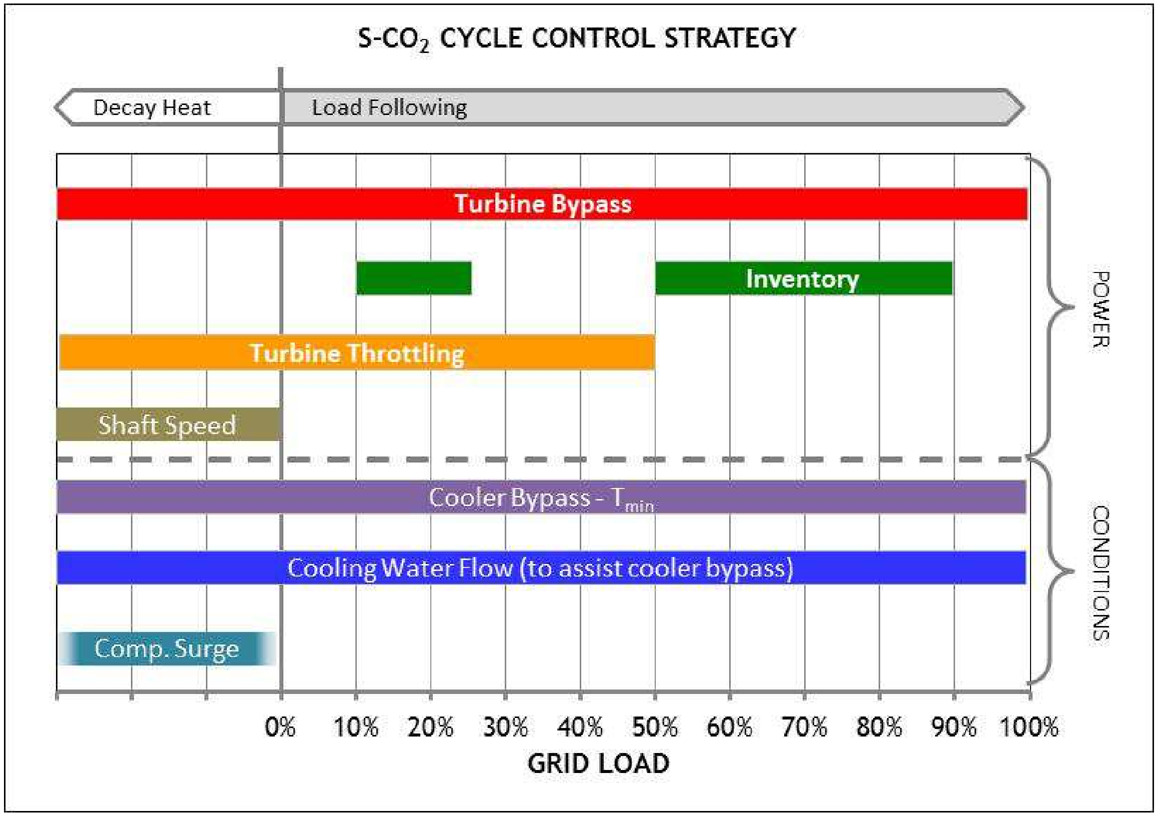
- Included into transient PDC equations
- Relies on combination of control mechanism
  - Turbine bypass [17]
    - Fastest power control (on pressure and flow)
    - Least efficient
  - Inventory control [18]
    - The most efficient (preserves TM velocity triangles for ideal gas)
    - Slow (introduce disturbance to compressor conditions)
    - Limited by tank volume
    - Decreases compressor surge margin
  - Turbine throttling [16]
    - More efficient than TBP, but less efficient than INV
    - Introduces an extra pressure rise with valve closing (not good for full pressure)
  - Cooler bypass [19]
  - Cooling water flow rate [14]
  - Compressor surge control



"Recent Developments in S-CO2 Cycle Dynamic Modeling and Analysis at ANL" by A. Moisseytsev, 4th S-CO2 Symposium, Pittsburgh, PA, September 9-10, 2014

$S\text{-}CO_2$ Cycle Control: **Control Strategy**

- Use inventory control when possible
  - Subject to storage tank volume limitation
- Turbine throttling
  - Outside INV range
- Turbine bypass for small load changes and fine-tuning
- Minimum temperature control
  - Always
- Shaft speed control
  - For decay heat removal
  - After disconnection from the grid
- Compressor surge control
  - When needed
  - Low power



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Demonstration of S-CO_2 Cycle Control with PDC

- Simulation in two stages
  - First stage: Load following from 100% down to 0%
  - Second Stage: Transition to decay heat removal

First Stage

- The electrical grid demand was set to reduce linearly at 5%/min rate from 100% to 0%
  - 1,200 s transient time
  - The only external input
- S-CO_2 cycle automatic controls adjust the conditions on the BOP side to maintain balance between the net generator output and the grid demand
- Autonomous reactor operation is assumed
  - Sodium-cooled fast reactor (ABR-1000)
  - No reactor power control by control rods
    - Only rely on reactivity feedbacks
  - No control of primary and intermediate pumps

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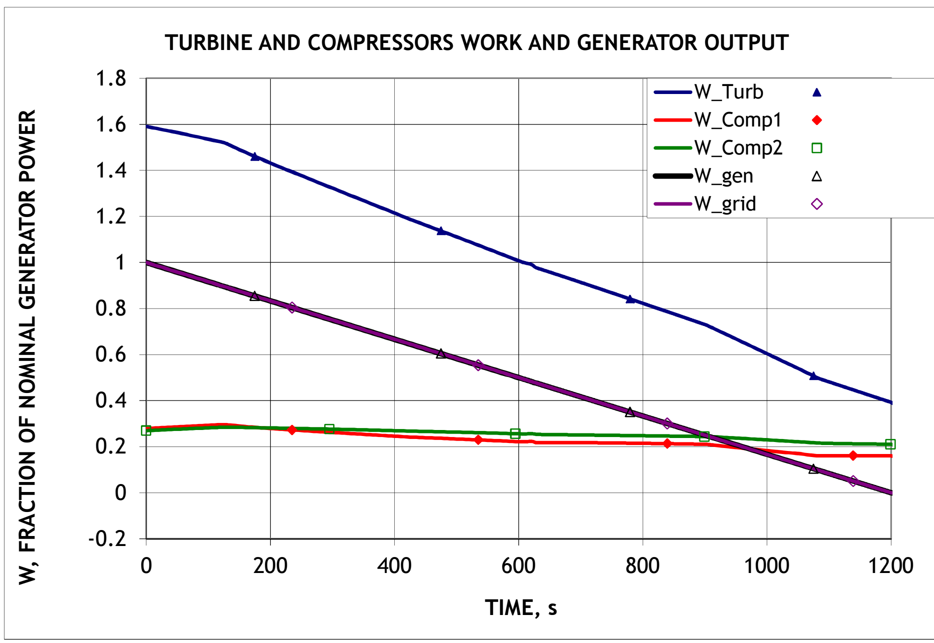
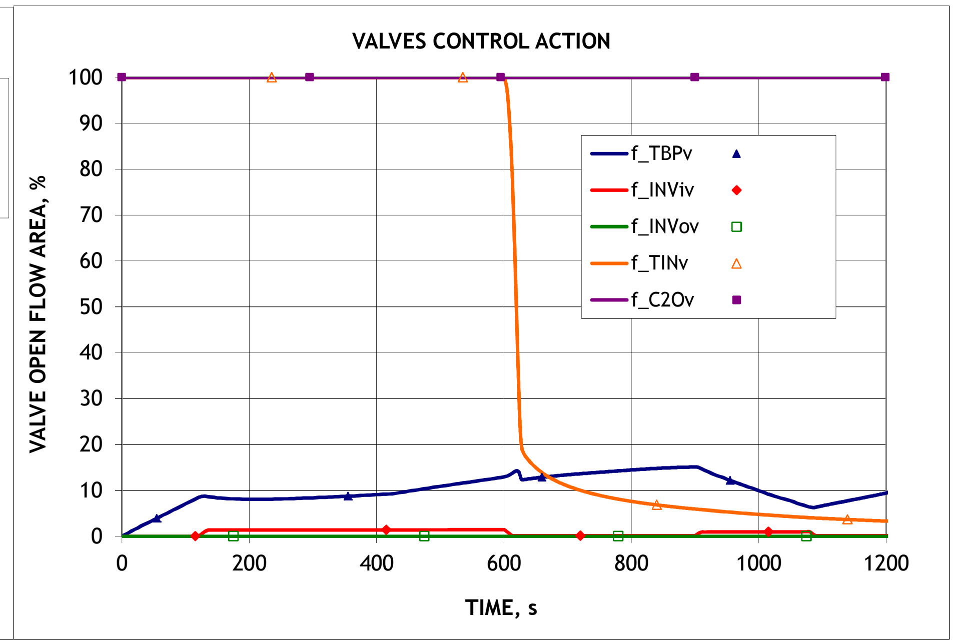
Results of Transient Simulations: *Load Following*

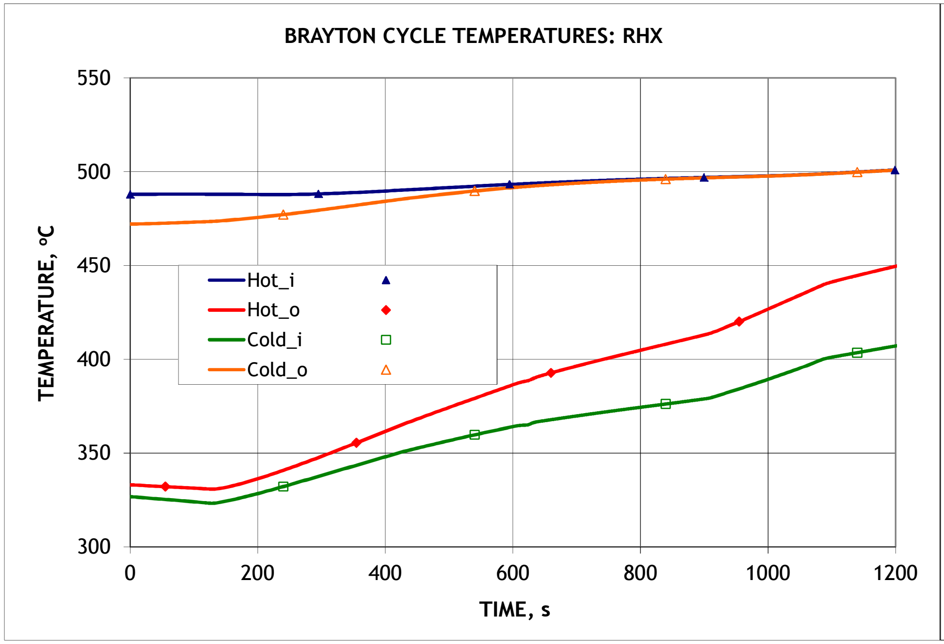
- Grid demand decreases linearly to 0 (external input)
- Net generator output follows the grid demand very closely
  - Achieved by control actions on S-CO_2 side

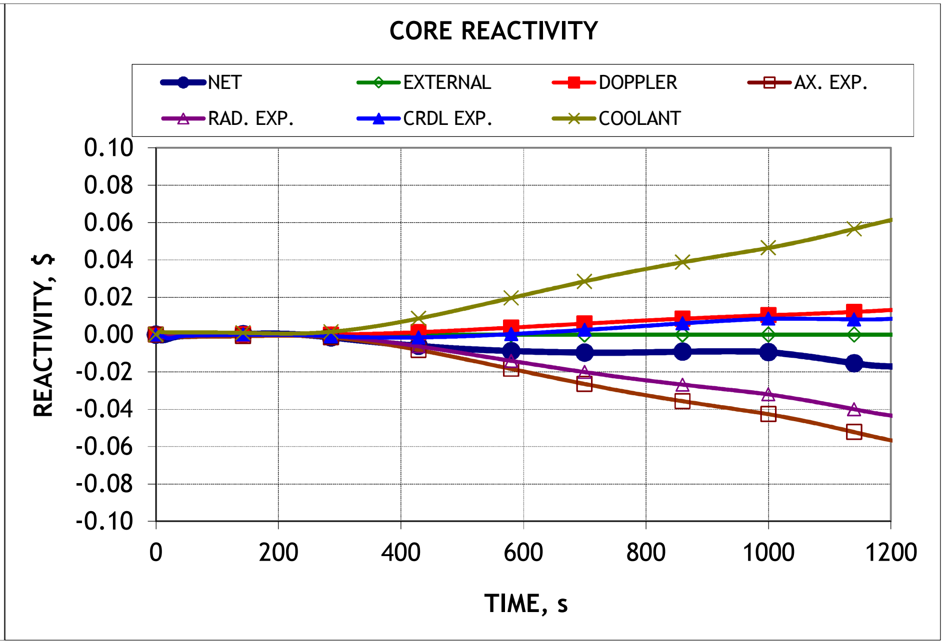




Results of Transient Simulations: *Load Following*

- Reduced heat removal by CO_2 affects the temperatures on the sodium side of Na-CO_2 HX
  - Sodium inlet temperature is defined by heat balance on the reactor side
- On the reactor side, changing intermediate and then primary loop temperatures introduce reactivity to the core





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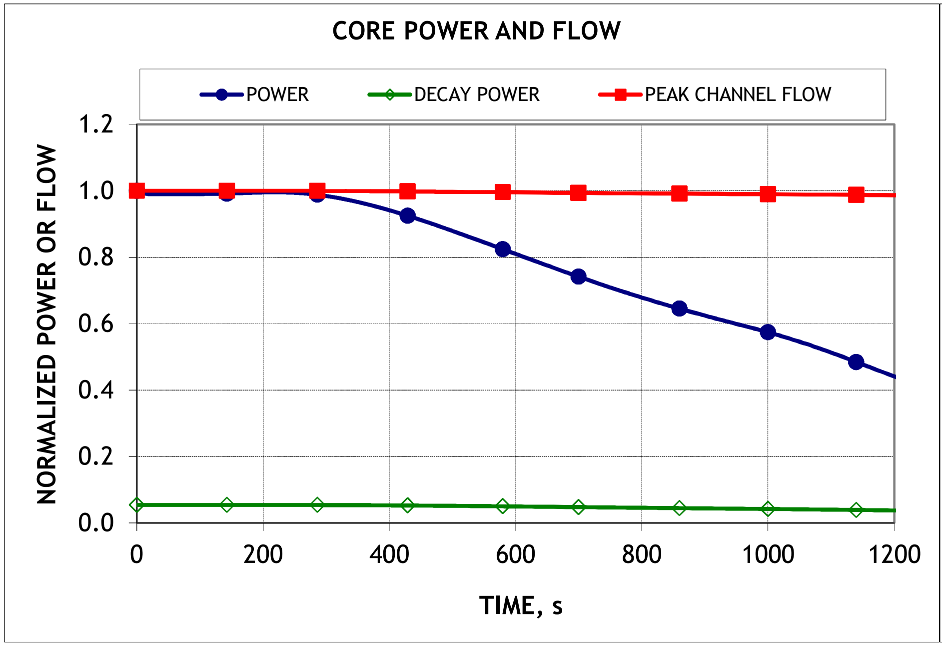
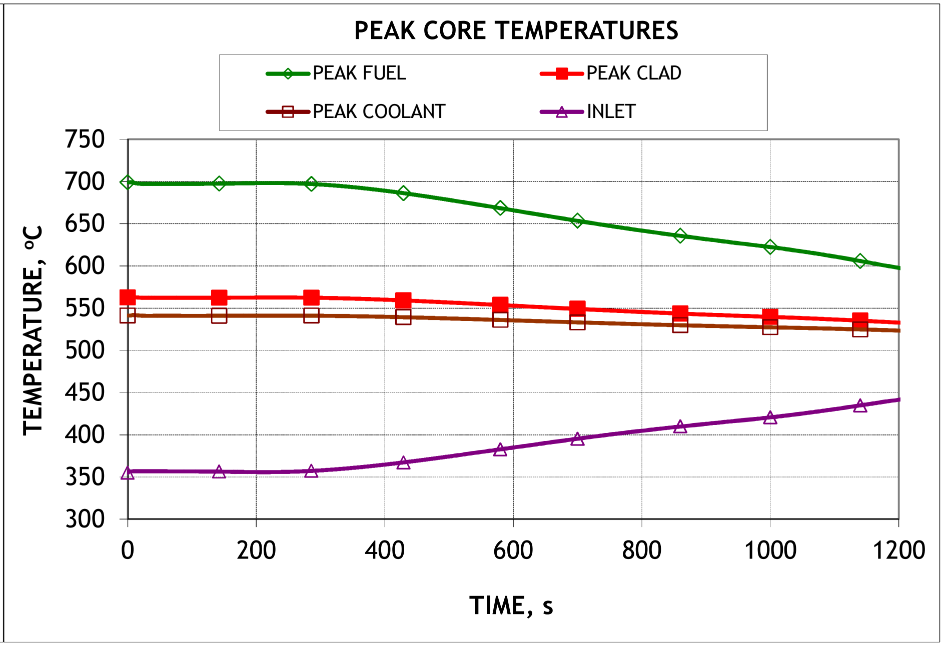
Results of Transient Simulations: *Load Following*

- The net effect of reactivity feedbacks is reduction of reactor power
  - Which closely follows the heat removal by CO_2 side
  - Even without active reactor power control
- The peak reactor temperatures stay below the nominal values
  - Result of strong negative reactivity feedbacks of ABR-1000 SFR core



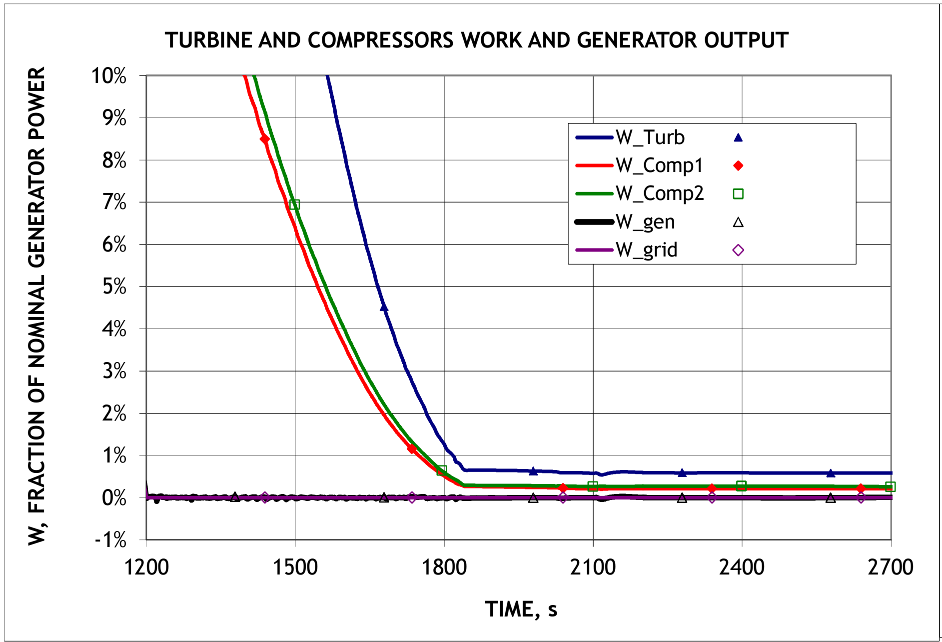


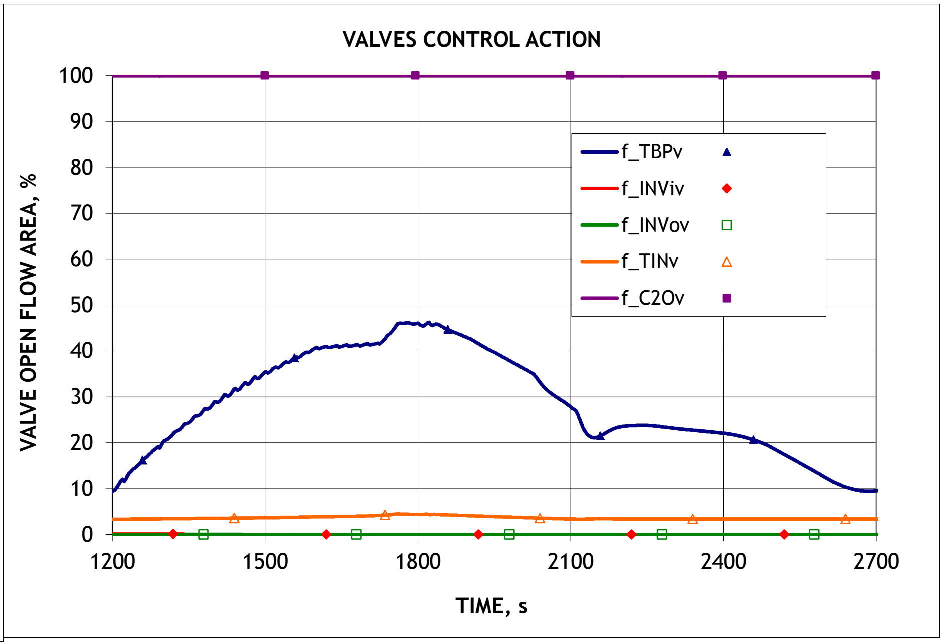
Transition to the Decay Heat Removal Mode

- Goal: find S-CO_2 cycle control which would allow plant operation at low reactor power
  - 6% or less
- Simulation was continued after the generator power reached 0% level
  - Same transient, Stage 2 starts at 1,200 s
- Generator is assumed to be disconnected from the grid
  - Zero grid demand
  - Ideally, the control system would maintain zero net generator output
    - If there is enough reserve power in turbine to drive the compressors
  - Turbomachinery shaft speed is assumed to reduce linearly to 20%
- No other changes in external input
  - Still autonomous reactor operation
- Minimum temperature control is no longer required to maintain minimum temperature at design point
  - As long as the temperature stays above the critical value

Results of Transient Simulations:
Transition to Decay Heat

- Slowing down shaft reduces both turbine and compressors work
  - Still, turbine provides sufficient power to drive the compressors
  - Zero net generator output is maintained
- The automatic cycle control maintains zero generator power
  - To match zero load demand

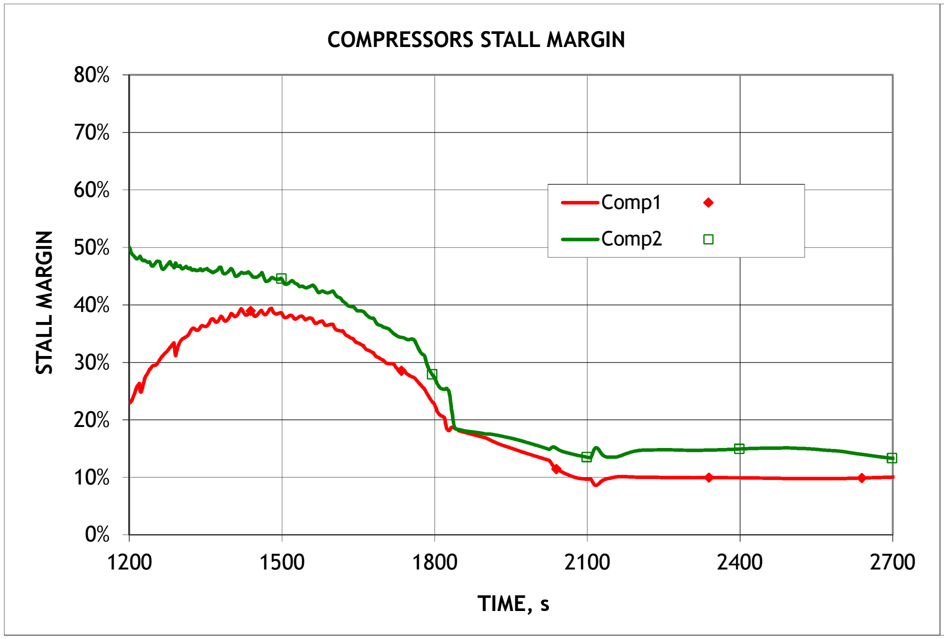


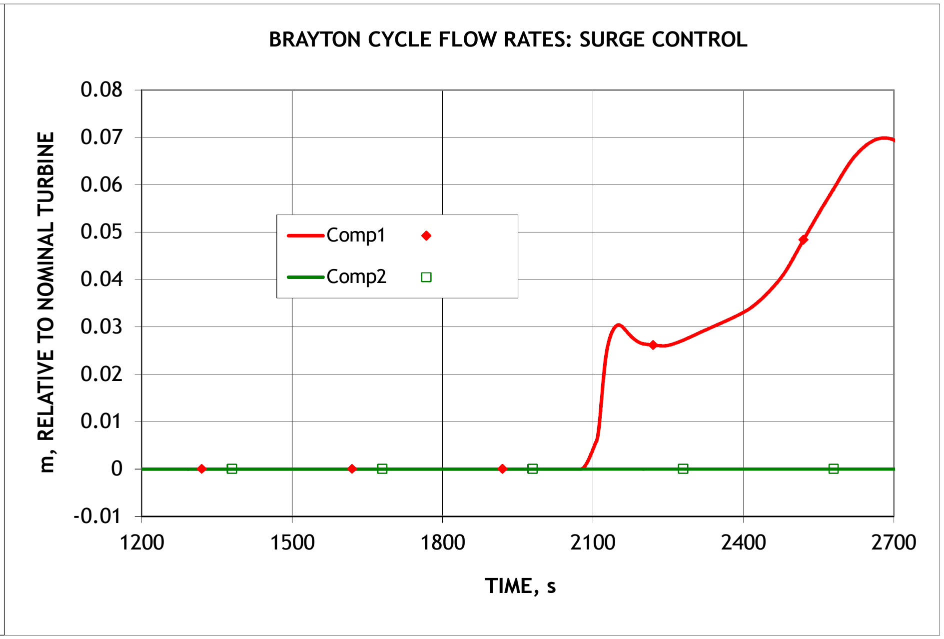


Results of Transient Simulations:

Transition to Decay Heat

- Compressor surge/stall approach is detected at about 2,100 s
  - Triggering surge control flow
  - Still, the flow is not too high to increase the compressor work significantly

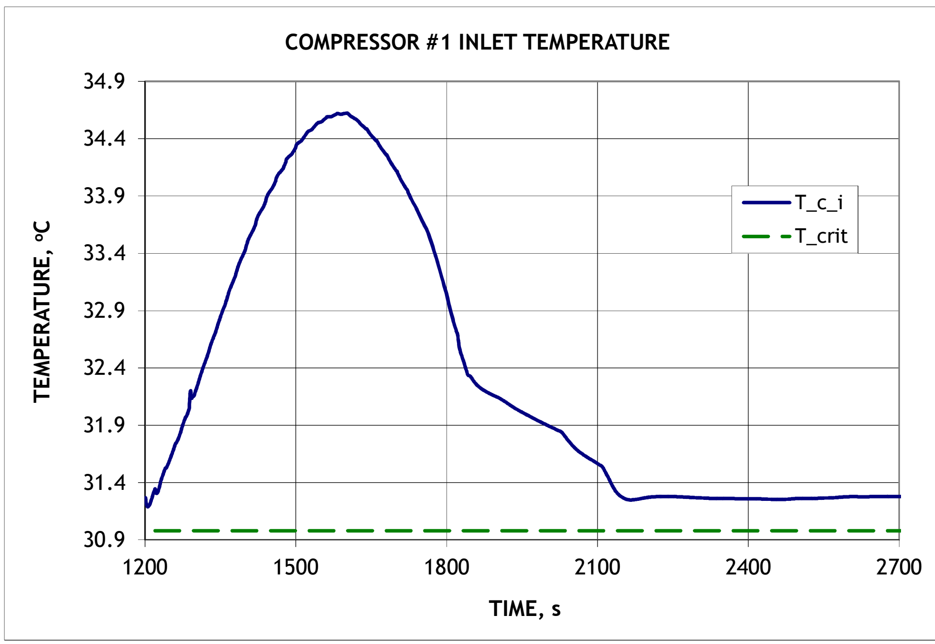


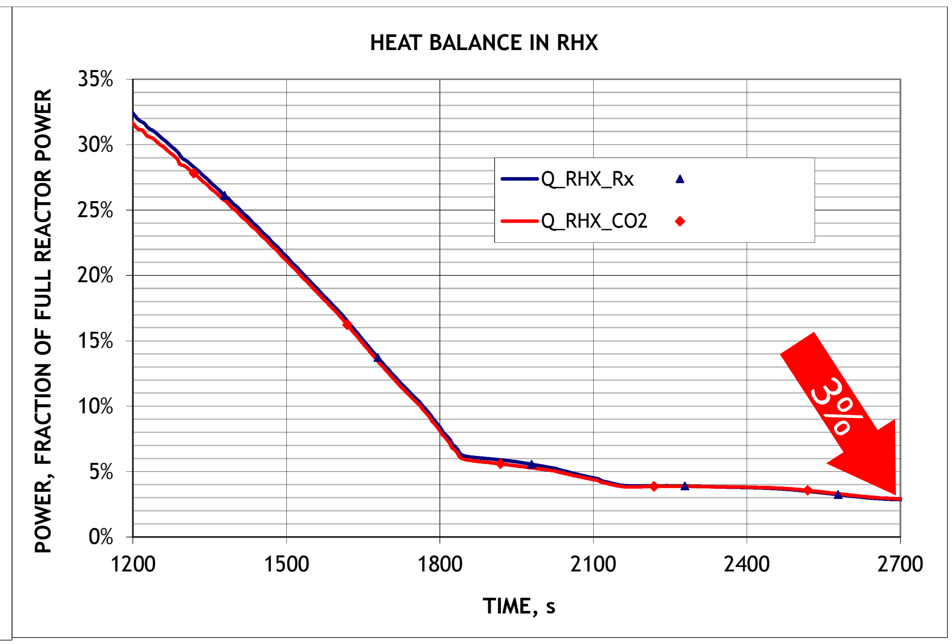


Results of Transient Simulations:
Transition to Decay Heat

- Temperatures above the critical point are maintained
  - Even with disabled cooler bypass control

- The heat removal rate by the cycle reduces to about 3% nominal

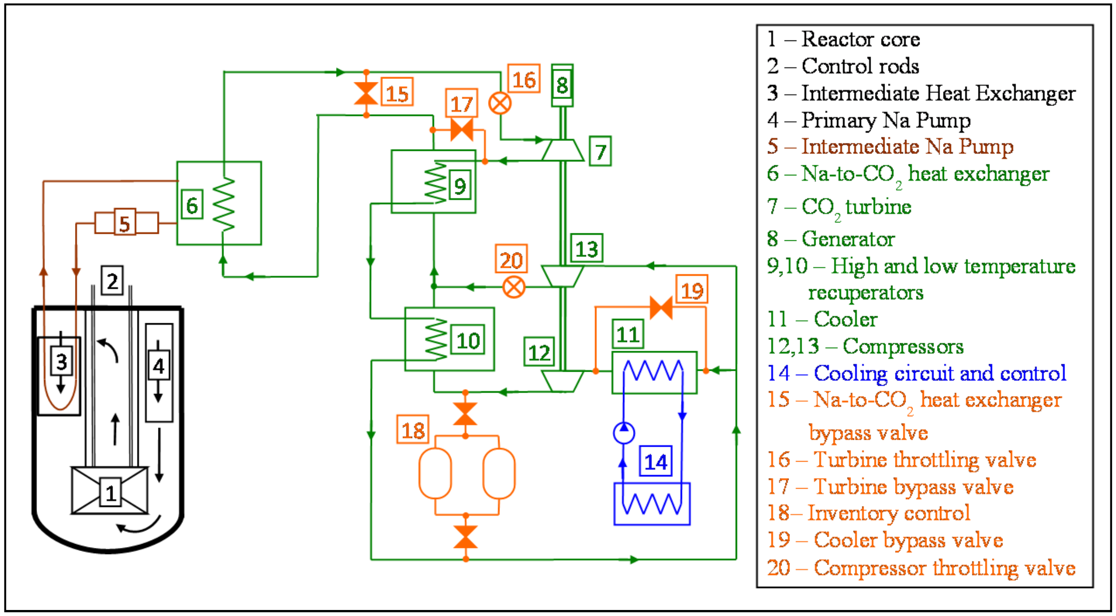




S-CO_2 Cycle Control with Active Reactor Control

Active Reactor Control in PDC-SAS4A/SASSYS-1 Codes

- In load following transients, the changes start on BOP side
  - E.g., turbine bypass valve opening in response to reducing grid load
  - Reactor "sees" changes through CO_2 heat removal variation (reduction) in the intermediate sodium-to-CO_2 reactor heat exchanger (RHX) 6
- To maintain intermediate sodium temperatures, sodium flow rate needs to be adjusted (reduced)
  - IHTS pump control 5
- This will affect IHX temperatures 3
  - Primary pump control 4
- With changed (low) primary coolant flow, reactor power needs to be changed
  - To maintain core-outlet temperature
  - By means of the control rod movements 2



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Reactor Control Logic

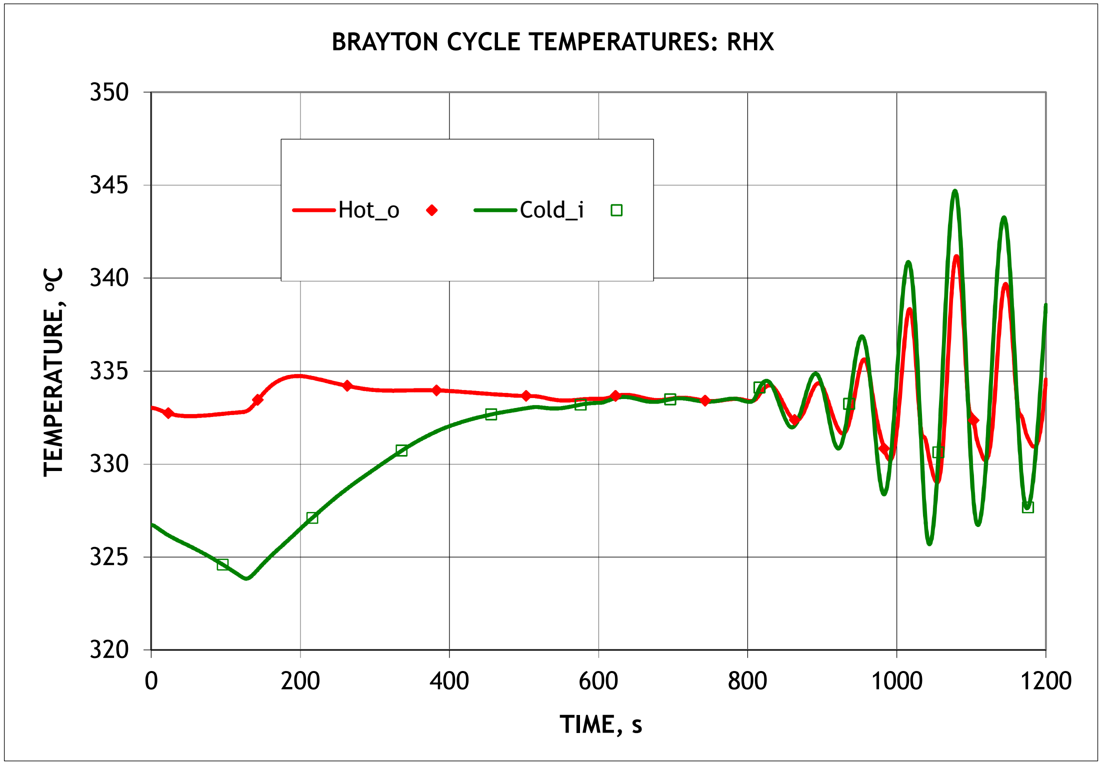
Controllable Parameter	Measured Value	Controlled By	Control
Intermediate loop cold-side temperatures	RHX-outlet Na temperature	Intermediate sodium flow rate	Intermediate sodium pump torque
Primary loop cold-side temperatures	IHX-outlet primary Na temperature	Primary sodium flow rate	Primary sodium pump torque
Hot-side temperatures	Core-average outlet temperature	Core power (reactivity)	External core reactivity

- Active reactor control logic was implemented in the PDC
  - Control action is communicated to SAS4A/SASSYS-1
- In ideal world, the temperatures will be maintained at steady-state levels everywhere
  - Power/flow=1
- In reality, system delays (and other limitations) will prevent that
  - Are there S-CO_2 cycle limitations?

Results of Active Reactor Control (40% linear load reduction)

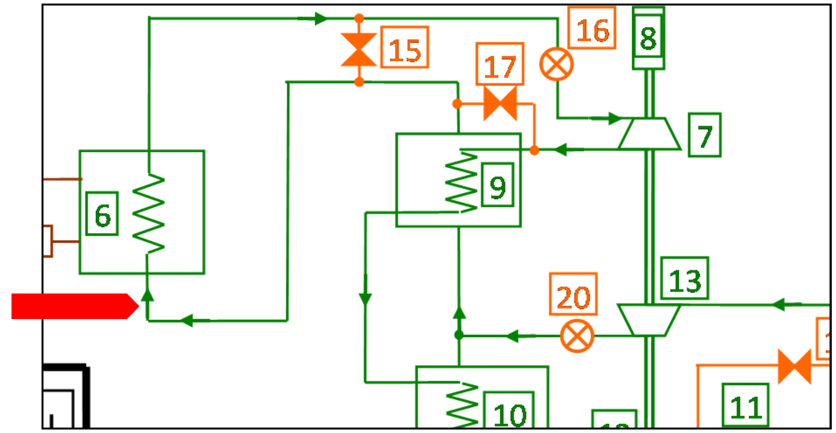
- Active control showed better results
  - Less temperature variation
  - Better power-to-flow ratio
  - Higher cycle efficiency

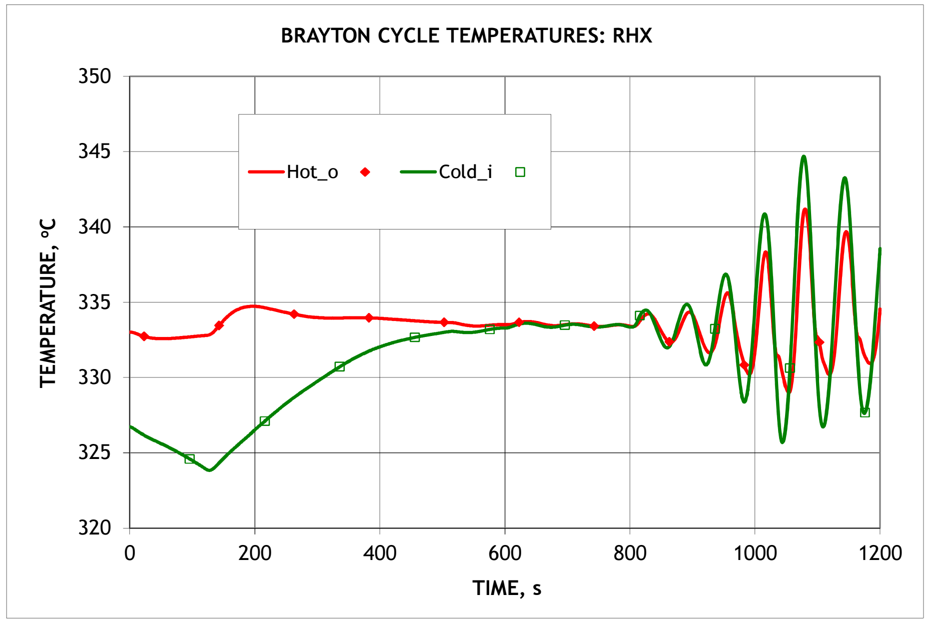
- However, these results were obtained for only 40% load reduction
  - What happens below 60% load?



CO_2 Temperature at RHX Inlet

- In highly-recuperated S-CO_2 cycle, RHX-inlet temperature is defined by HTR performance
- When flow rate increases, heat transfer in HTR is reduced, RHX-inlet temperature ↓
  - During turbine bypass
    - 0-120 s
- With decreasing flow rate, RHX-inlet temperature ↑
  - With inventory control
- *When CO_2 temperature at RHX cold end reaches steady-state value for sodium temperature, **ability to maintain that temperature is lost***





CO_2 Temperature at RHX Inlet

- Several approaches to control the temperature (prevent from increasing) were investigated
  - Reduced inventory control action
  - Recuperator bypass
  - Relaxed sodium temperature requirements
  - Reduced core-outlet temperature

- Control on S-CO_2 cycle side resulted in too low cycle efficiency
  - Plus, there are additional limits
- Results with relaxed temperature limits are acceptable
  - If high structure temperatures (say, 400 ^oC) can be tolerated
- Reduced core-outlet temperature is recommended as a preferred option
  - All temperature limits are satisfied
    - There are short-term effects
  - Cycle efficiency drop from lower turbine-inlet temperature is not significant

ANL Plant Dynamics Code Validation

ANL Plant Dynamics Code V&V History

- $S\text{-}CO_2$ cycle has never been commercially operated

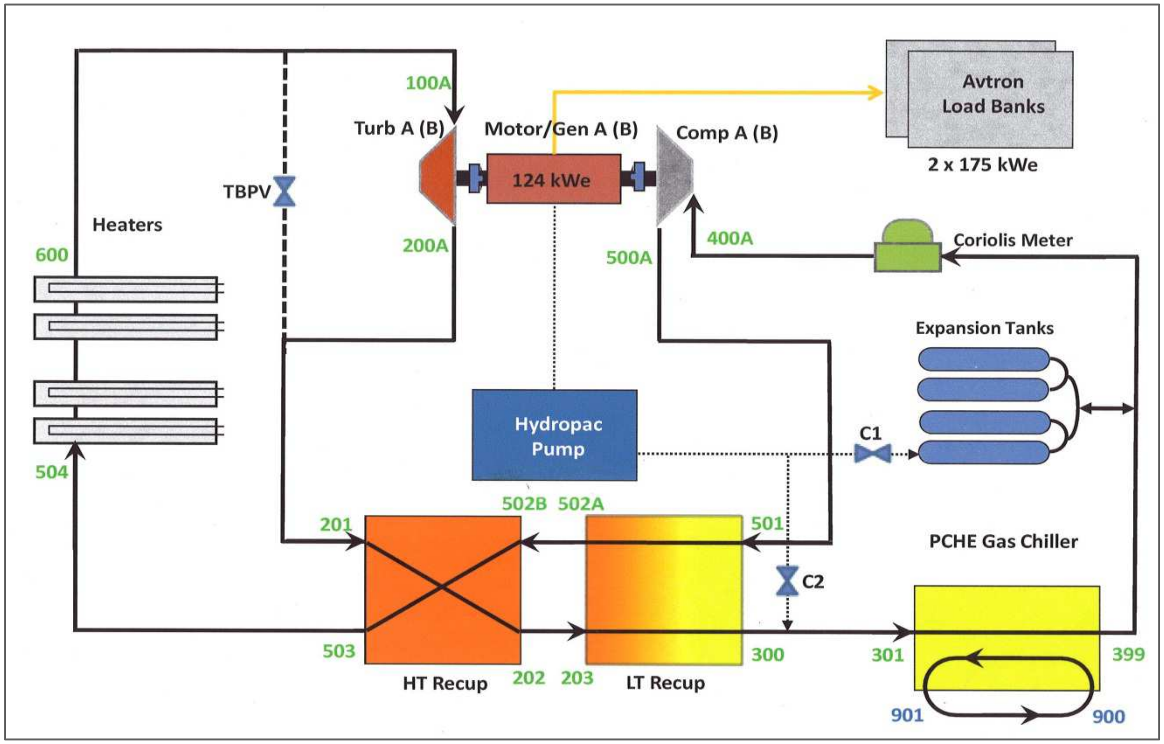
- Earlier V&V was limited to benchmark calculations against similar codes elsewhere

- Later, limited code validation on individual components
  - Heat exchangers (PCHE test loop at ANL)
  - Turbomachinery (Ideal gas loop at SNL)
  - Small-scale $S\text{-}CO_2$ compressor test loop at Barber-Nichols Inc.

- Recently, Barber-Nichols, Inc. (BNI) and Sandia National Labs (SNL) constructed and operated small-scale closed split-flow $S\text{-}CO_2$ cycle loop
  - SNL Loop will provide a configuration for PDC testing and validation of modeling
    - CO_2 working fluid
    - Equipment designed to operate close to the critical point
    - Recompression cycle configuration
  - Recent PDC validation effort is focused on simulating the SNL Loop and data

July 14, 2011 SNL Loop Setup

- Single TAC
- Two recuperators
  - HTR is “overdesigned” for this setup -> very little, if any, heat transfer in LTR
  - Only HTR is simulated in the PDC
- 4 heaters
  - 390 kW input limit at BNI facility



SNL Loop Data and Modeling

- Some specifics of the experimental setup (for model validation purposes) were identified
  - Significant heat loss in pipes and in turbine
    - The heat loss in turbine volute is not measured
  - The loop could not be run for a long time to achieve "perfect" heat balance
    - Required for steady-state initialization in the PDC
  - Lack of information on PCHE internal configuration
  - No water flow rate measurements
  - Temperature measurement uncertainty (1.1 ^{o}C) is significant

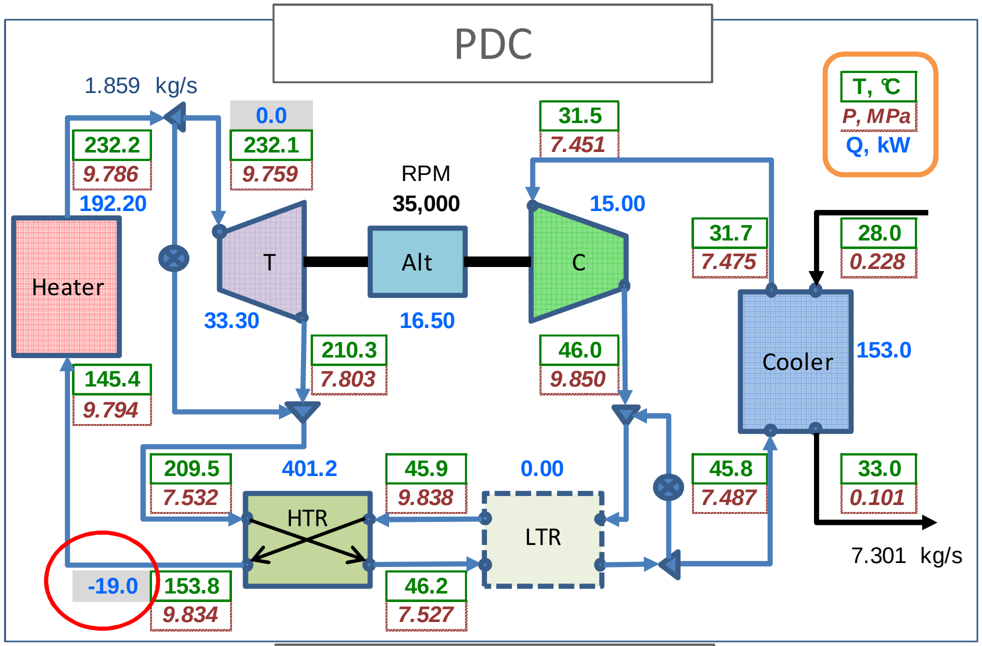
- Some features were dealt with modeling assumptions

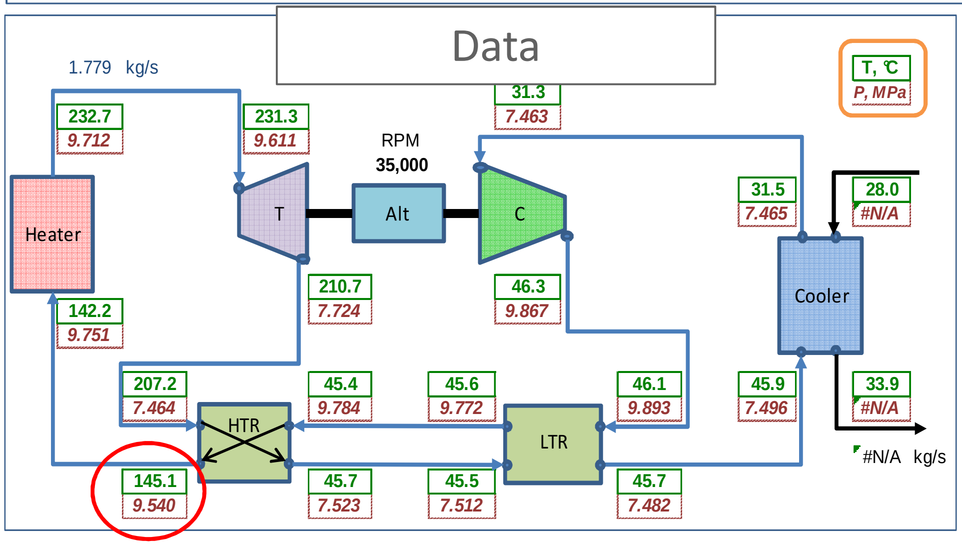
Transient Simulation: Assumptions

- The LTR was excluded from the PDC model
- The electrical heaters are simulated with shell-and-tube heat exchangers
  - Sodium flow on the hot side for the steady-state model
  - Direct heat input into the HX "tubes" in transients
- All of the heat losses in the system were simulated to occur in the HTR-heater pipe
  - Including turbomachinery heat loss
  - The amount of the heat loss was determined to achieve a heat balance throughout the system at steady-state conditions
  - In a transient, the heat loss is scaled with the changing CO_2 temperatures in the pipe
- Other than the heat loss, no heat transfer is simulated in the pipes in the PDC
  - Also includes the absence of heat exchange between the CO_2 and the pipe walls
- The TAC drain flow is not included into the PDC steady-state and transient models

Steady-State Calculations

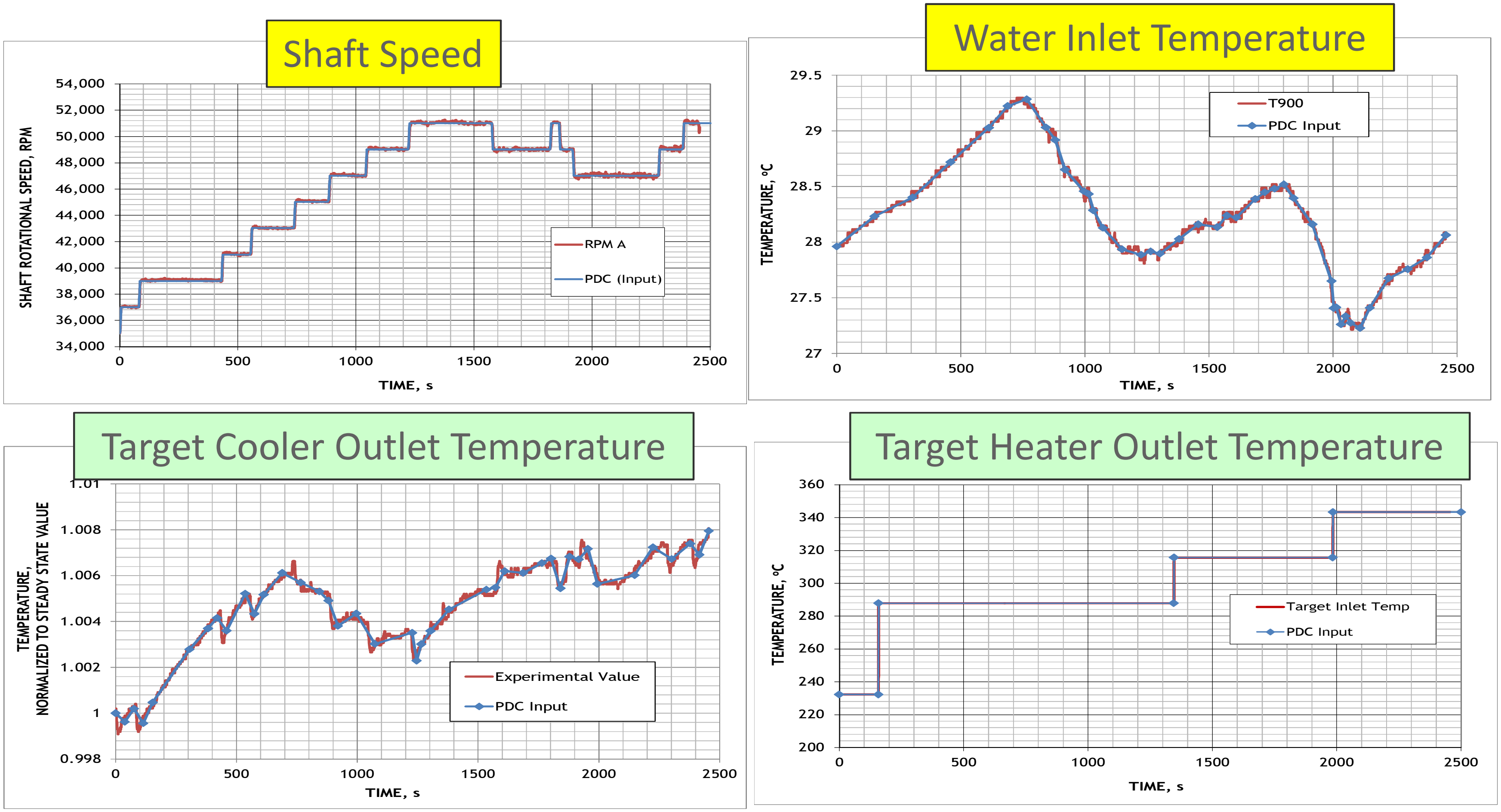
- Good agreement was achieved for steady-state
  - Required significant heat loss simulation (19 kW) at heater inlet
    - Simulates **all** heat losses in the cycle
    - Also compensates for not achieving perfect heat balance in HTR by 3356 s
  - Skipping LTR did not affect temperatures much





Dynamic Simulation of SNL S-CO_2 Loop with the PDC

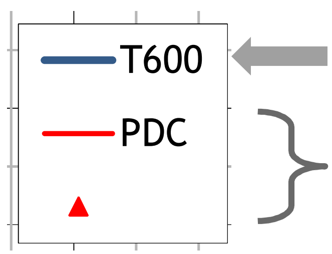
- Transient is defined by the experimental data through the external input:



- Initial conditions: “steady-state” at 3356 s

Transient Results Presentation

- Compare **all** available experimental measurements with the corresponding PDC predictions
  - Temperatures, pressures, density, flow rates
- The following slides show such comparisons for each individual parameter

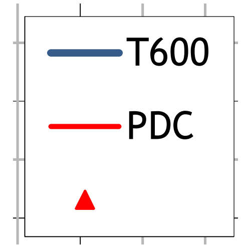


Measured data (e.g., Temperature at point 600)

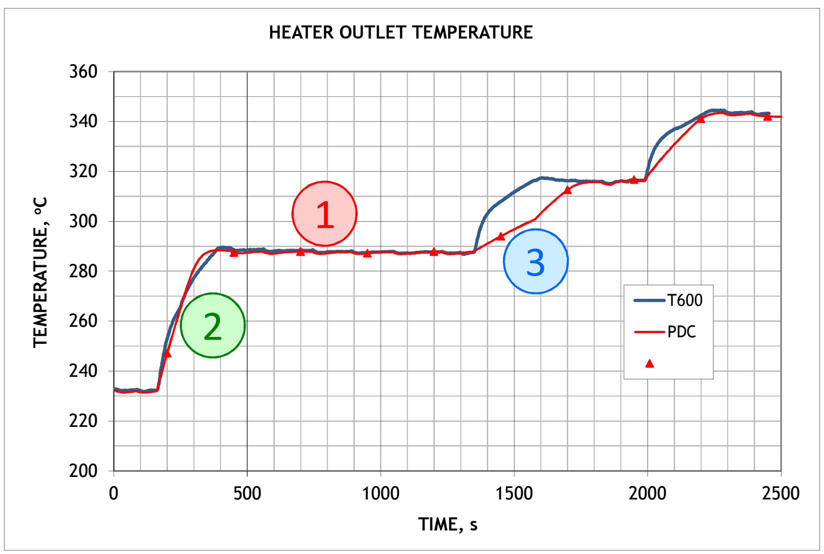
Corresponding code results

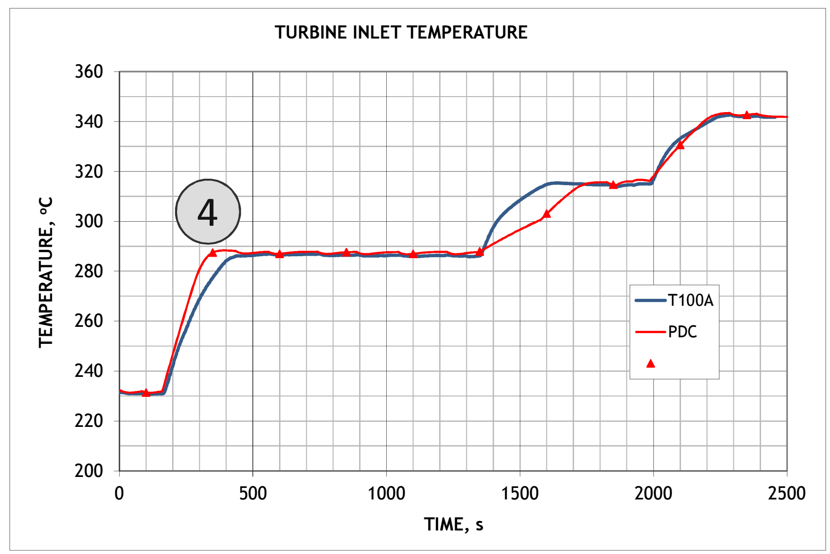
- Few results are presented here
  - Differences are briefly discussed
  - See the paper for more detailed comparison

Transient Results Comparison



- **Heater outlet temperature** is predicted very accurately (1)
  - Results of the automatic control
  - Short-term behavior is achieved by control's PID coefficients optimization (2)
  - In some cases, there is not enough reserve capacity in the heater (3)
    - Discussed below
- **Turbine inlet temperature** is very close to the heater outlet
  - There is, however, a somewhat noticeable time delay in the experimental data (4)
    - Not showing in the PDC – result of not simulating pipe heat capacity





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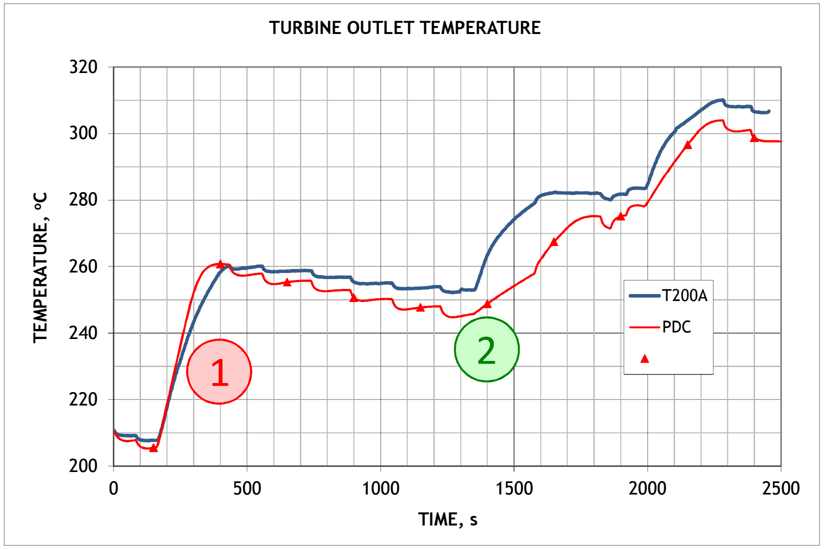
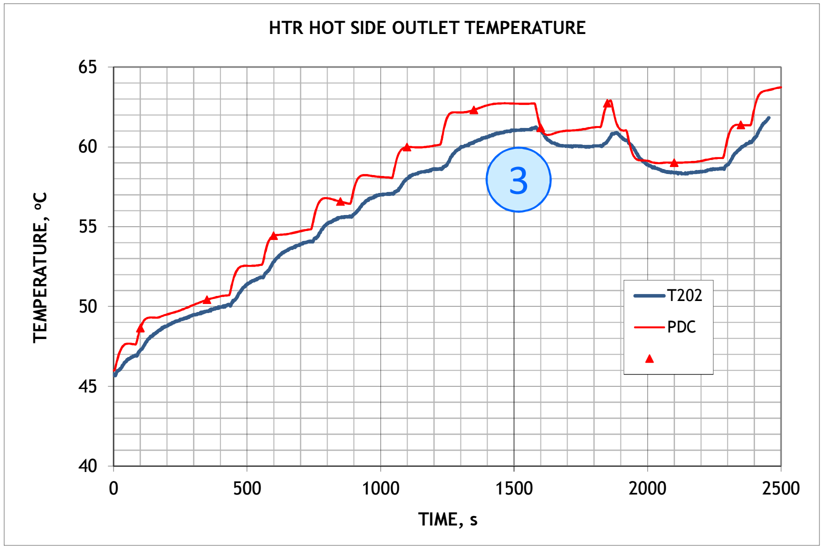
Transient Results Comparison

- **Turbine outlet temperature** is predicted accurately earlier in the transient (1)
  - But diverges with higher turbine speed (2)
    - Overprediction of turbine performance at higher speeds
- **HTR hot side outlet temperature** is slightly overpredicted by the PDC
  - Overprediction of HTR performance
  - Maximum difference is only 1.5 °C (3)
    - Measurement ΔT = 1.1 °C





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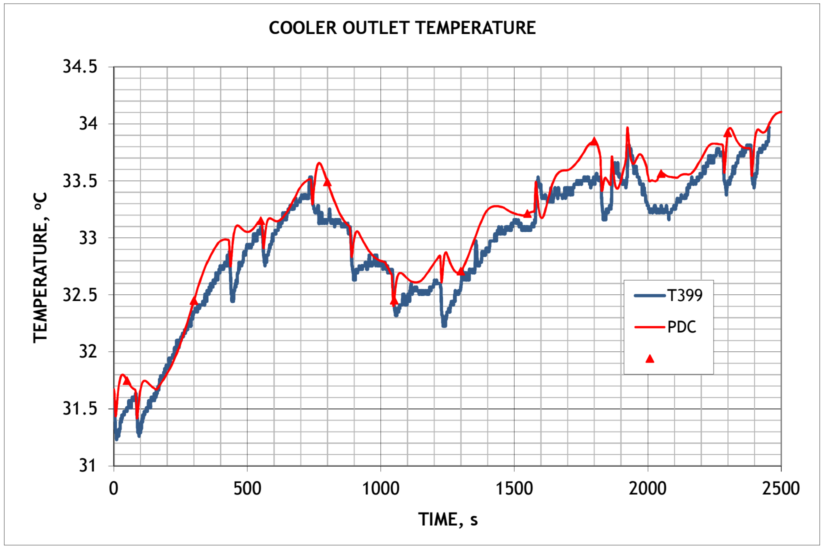
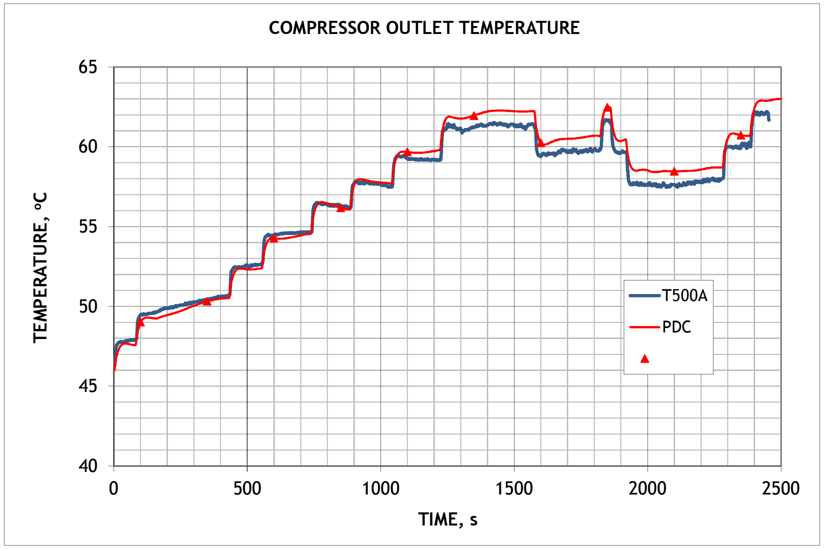
Transient Results Comparison

- **Cooler outlet temperature** is very close
  - Maximum difference is only 0.3 °C
  - Measured temperature was an input for PDC
    - Verifies control performance, not necessarily cooler model
- **Compressor outlet temperature** is predicted very accurately
  - Maximum difference is only 1 °C
    - Within the measurement uncertainty





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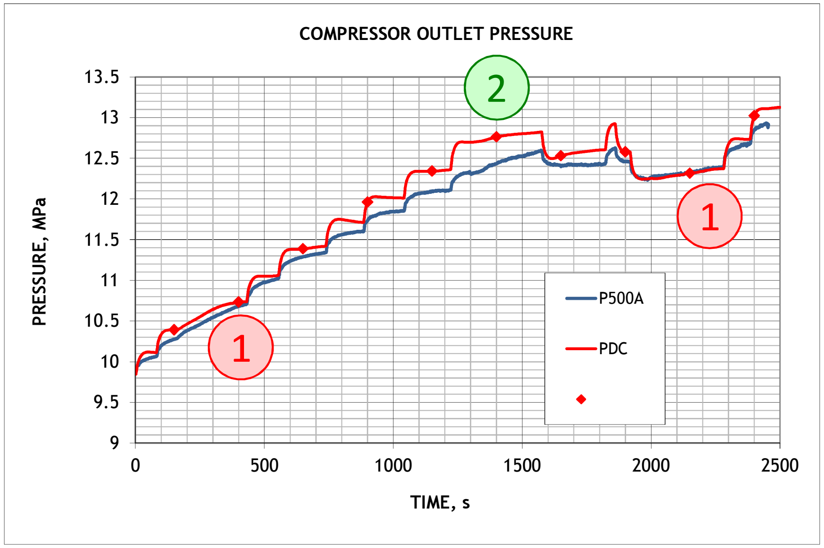
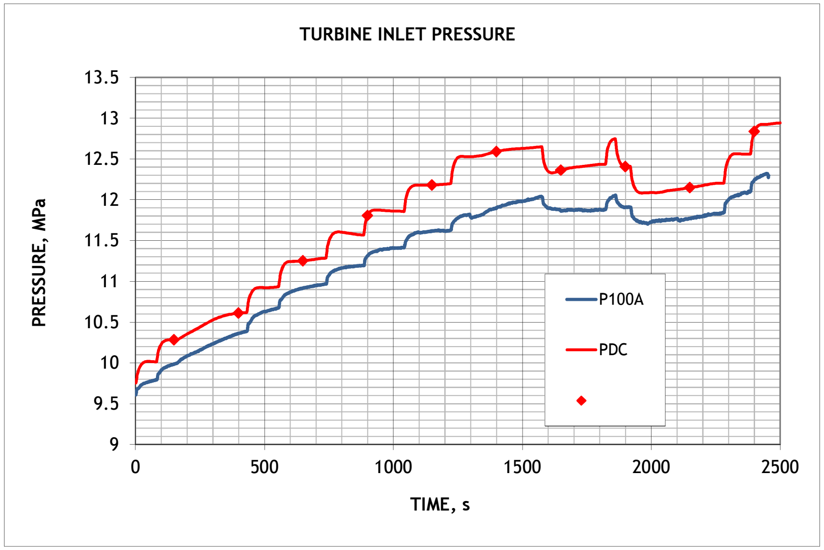
Transient Results Comparison

- **Compressor outlet pressure** is predicted accurately earlier and late in the transient (1)
  - Pressure is overpredicted in the middle section (2)
    - High rotational speeds
- **Turbine inlet pressure** is consistently overpredicted by the code
  - In part, due to compressor performance overprediction
  - Also, underprediction of the pressure drops
    - LTR

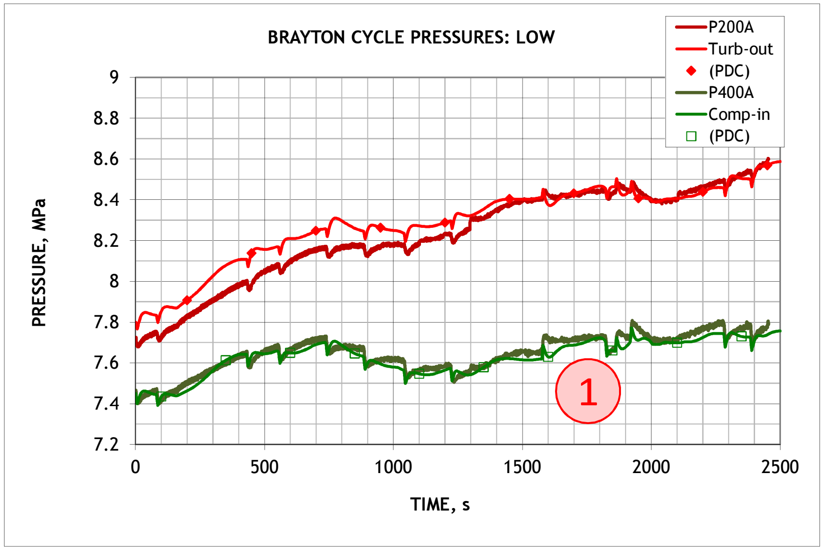


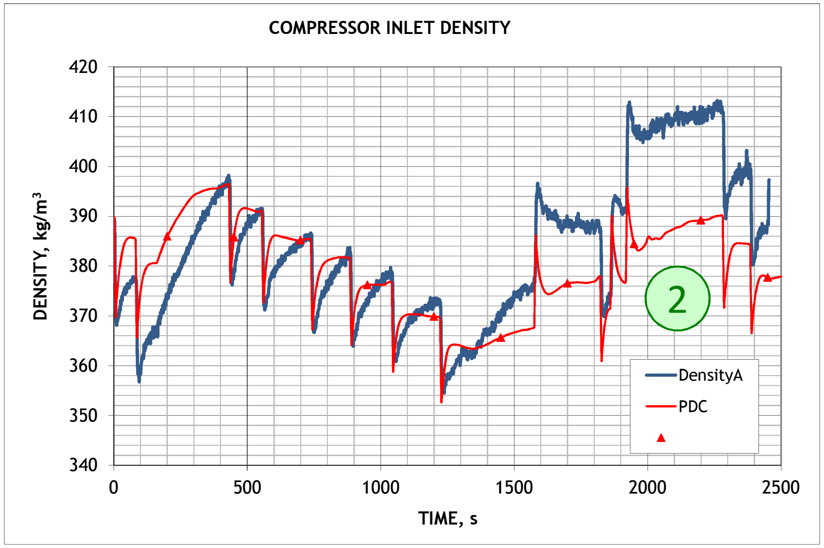


"Recent Developments in S-CO2 Cycle Dynamic Modeling and Analysis at ANL" by A. Moisseytsev, 4th S-CO2 Symposium, Pittsburgh, PA, September 9-10, 2014

Transient Results Comparison

- **Low side pressures** show much better agreement
  - Especially, for the compressor inlet (1)
- **Compressor inlet density** prediction is close
  - The only density measurement in the loop
  - Some difference at later stages are possibly due to difference in the cooler-outlet temperature (2)

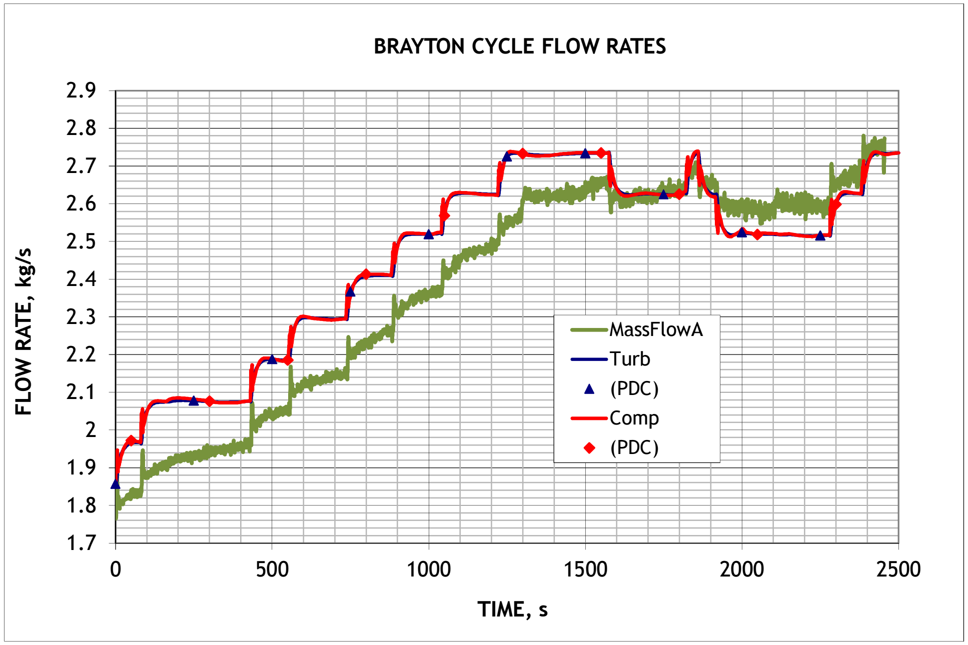




"Recent Developments in S-CO2 Cycle Dynamic Modeling and Analysis at ANL" by A. Moisseytsev, 4th S-CO2 Symposium, Pittsburgh, PA, September 9-10, 2014

Transient Results Comparison

- **CO_2 flow rate** is overpredicted by the code for most of the transient
  - By about 5%
  - Consistent with steady-state results
    - Flow rate was calculated from the heat balance
    - Perfect heat balance was not achieved at 3356 s
  - Also, code predicts much faster change in the flow rate
    - Possibly, due to heat capacity of turbomachinery, which is ignored in the PDC by virtue of using the turbomachinery maps



"Recent Developments in S-CO2 Cycle Dynamic Modeling and Analysis at ANL" by A. Moisseytsev, 4th S-CO2 Symposium, Pittsburgh, PA, September 9-10, 2014

Lessons Learned from SNL Loop Simulation (So Far)

- The PDC transient results are close to the experimental data
  - The existing modeling capabilities may be sufficient
- Lack of information on PCHE internal configuration
  - E.g., channel diameter, zigzag angle
- The loop could not be run for a long time to achieve "perfect" heat balance
  - Required for steady-state initialization in the PDC
  - "Steady-state" at ***supercritical*** conditions is highly recommended
- Heat loss in pipes, recuperators, and turbine is difficult to account for
  - The heat loss in turbine volute is not measured
- Water flow rate measurements are needed for cooler model validation
- Complete understanding of the control action is required for modeling
- Temperature measurement uncertainty (1.1 ^{o}C) is significant
  - Density is only measured at the compressor inlet
- Turbomachinery performance is overpredicted at higher speeds
  - Need loss correlations better suited for small-scale TM

➢ Note that all of these effects are specific to the SNL small-scale loop and become negligible for commercial-scale S-CO_2 cycles

Summary

- Plant Dynamics Code is developed at ANL for analysis of S-CO_2 cycles
  - Addresses specific features of the cycle
- A new approach was developed to couple the PDC with SAS4A/SASSYS-1
  - Coupled reactor-BOP calculations
- A control strategy for the S-CO_2 Brayton cycle has been developed
  - Combination of various control mechanisms
  - Enables load following from 100% to 0% and transition to decay heat removal mode
- Active reactor control is implemented in the coupled PDC-SAS4A/SASSYS-1 codes
  - Aspects of S-CO_2 cycle operation on the reactor control are discovered and investigated
- PDC validation is ongoing
  - Effort is concentrated on modeling the SNL S-CO_2 Loop
  - Lessons learned regarding simulation of the experimental facilities