CONTROL OF MICRO-REACTORS

ANTON MOISSEYTSEV
Argonne National Laboratory

Advanced Control Systems Workshop
Argonne National Laboratory
July 12, 2023

GOALS

- Analysis of flexible operation of a micro-reactor
  - Load following

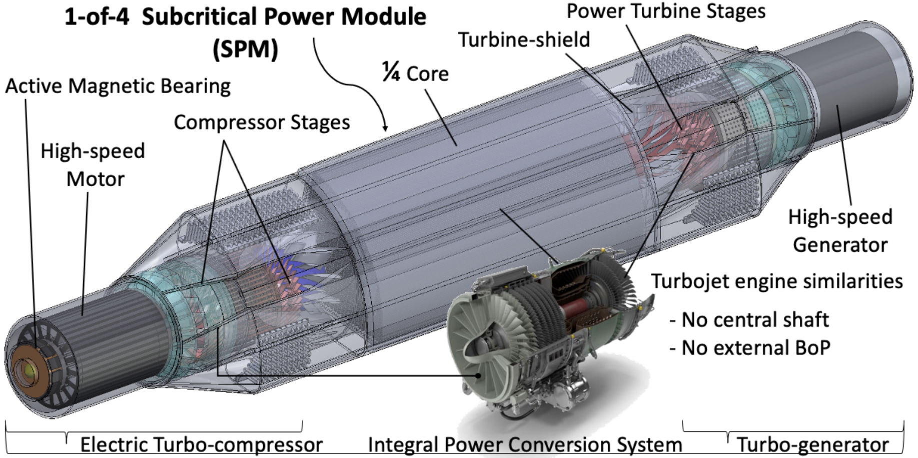
- Development and simulation of control strategy

- Using Argonne system analysis tool
  - Plant Dynamics Code

- Calculations are carried out for Holos-Quad micro-reactor

HOLOS-QUAD MICRO-REACTOR

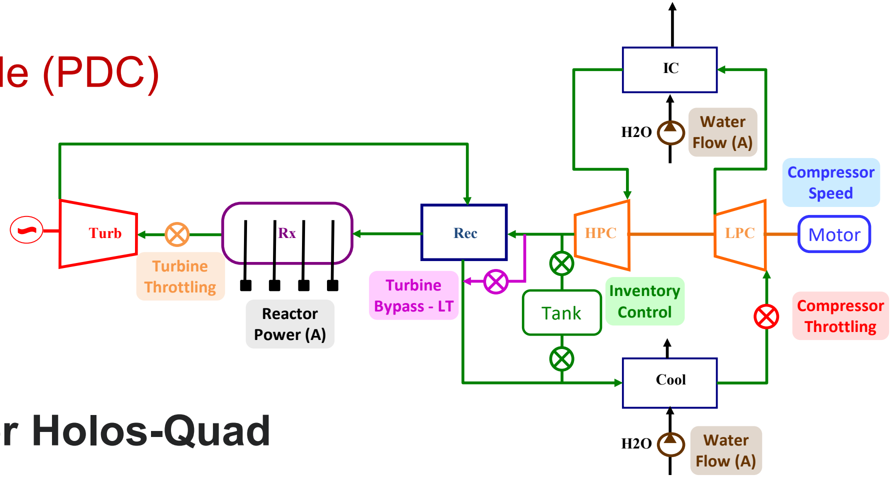
- Holos-Quad micro-reactor concept developed by HolosGen LLC
  - High-temperature gas-cooled reactor
  - 4 neutron-coupled Subcritical Power Modules (SPMs)
  - 22 MW_{th} (10 MW_e)
  - Lifetime of 8 EFPY
- Each SPM integrates & seals its power conversion system
  - Inspired by turbojet engine
- Direct helium Brayton cycle for energy conversion



LOAD FOLLOWING ANALYSIS

- Goal: investigate Holos-Quad design capability for load following
  - Load following: ability to effectively operate at power output <100%
  - Target: match 10%/min grid/load demand change from 100% to 0% and back

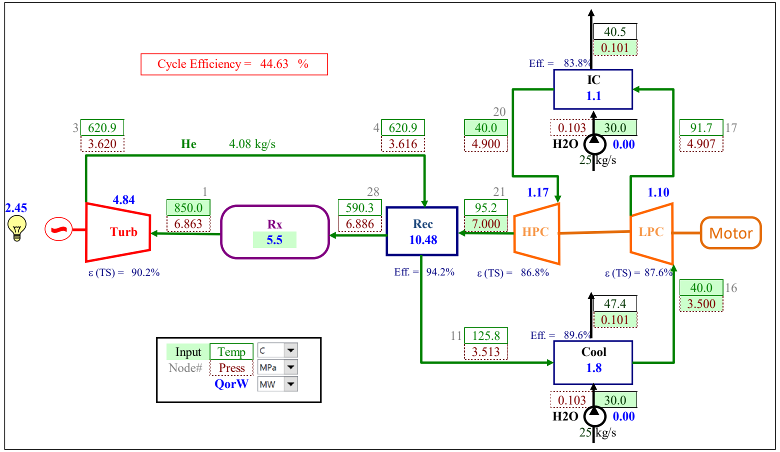
- Approach
  - Transient calculations
    - Simulated in ANL Plant Dynamics Code (PDC)
  - Integrated reactor/cycle analysis
  - Identify possible control mechanisms
  - Simulate and analyze LF by each control



➢ **Develop an optimal control strategy for Holos-Quad**

ANL PLANT DYNAMICS CODE (PDC)

- Developed at Argonne originally for supercritical CO_2 cycles
  - Special attention to complex CO_2 properties
  - Detailed solution
  - Copyrighted in 2018 by Argonne
  - Helium properties for Holos-Quad
- Steady-state analysis
  - Performance of each component (HXs, TM)
  - Integrated cycle performance (efficiency)
  - Piping pressure drop
  - Integrates TM design
- Dynamic calculations
  - Cycle control mechanisms and analysis
    - PID Controllers
  - HX thermal inertia and performance
  - TM off-design performance
  - Piping inertia and heat losses

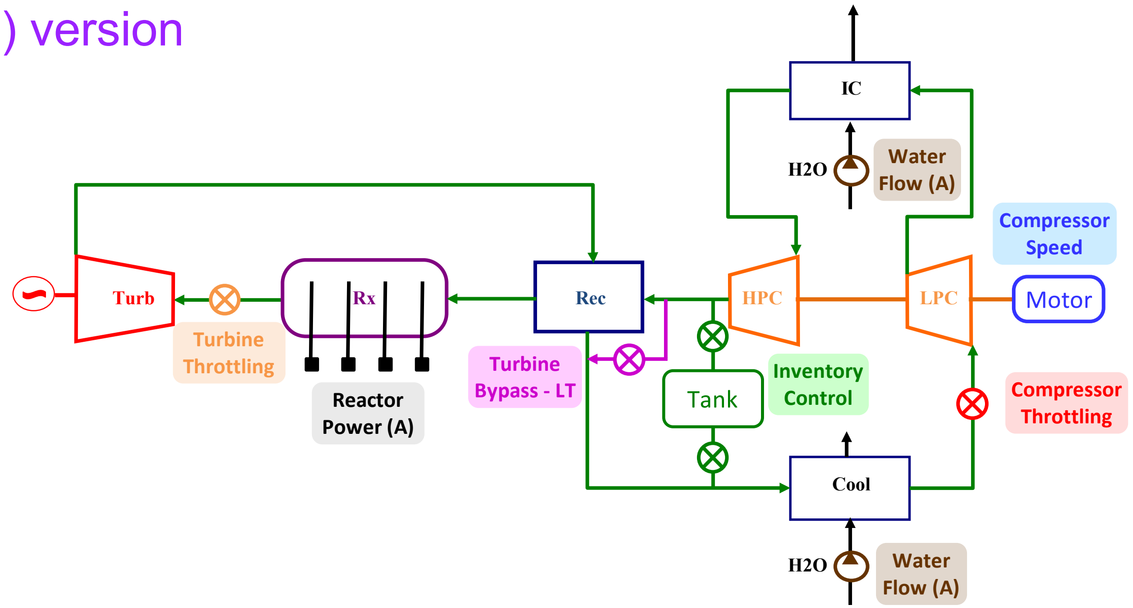


Argonne NATIONAL LABORATORY

HOLOS-QUAD PLANT CONTROL MECHANISMS

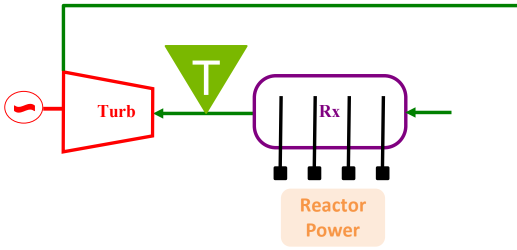
HOLOS-QUAD CONTROLS

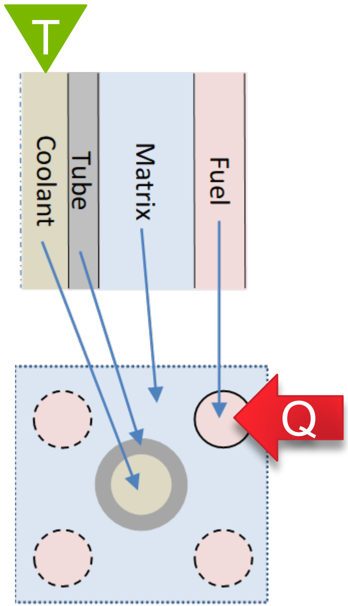
- **Factors all possible** (traditional) Brayton cycle controls
  - Bypass
    - Turbine bypass
    - Low Temperature (LT) version
  - Throttling
    - Turbine
    - Compressor
  - Inventory
- Holos-Quad specific
  - Compressor speed
- “External” controls
  - Reactor power
  - Water flow



EXTERNAL CONTROLS: REACTOR POWER

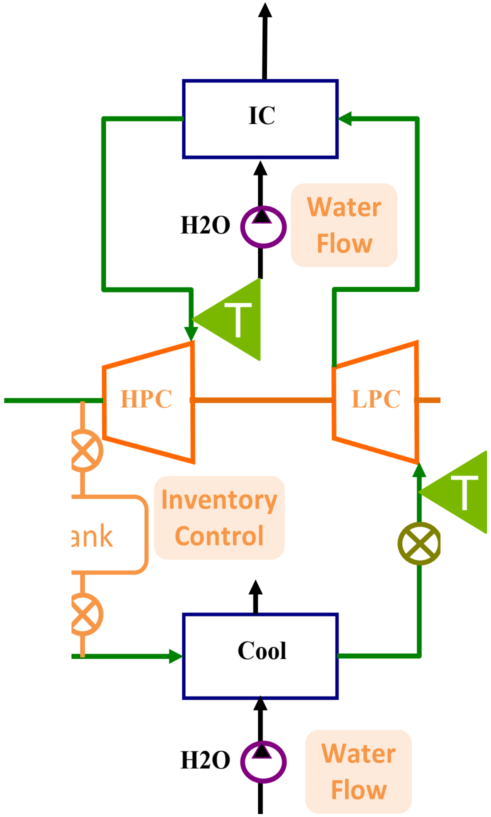
- Automatic control of Rx-outlet (turbine-inlet) temperature
  - By heat generation in fuel
  - PID controls
    - Optimized for step change in target temperature
  - Set to maintain 850 ^{o}C all the time
- Limits
  - +/- 50%/s
  - $\leq$110% nominal
- PDC model includes
  - Temperatures: coolant, tube, matrix (C), fuel
  - Heat capacities
  - Thermal resistances
- Required reactor power will be the code **output**





EXTERNAL CONTROL: WATER FLOW

- Automatic control of compressor-inlet temperatures
  - By water pump head
  - PID controls
    - Optimized for step change in target temperature
  - Set to maintain 40 °C all the time
- Independent for two coolers/compressors
- Limits
  - +/- 10%/s
  - ≥0.5%, ≤200% nominal head



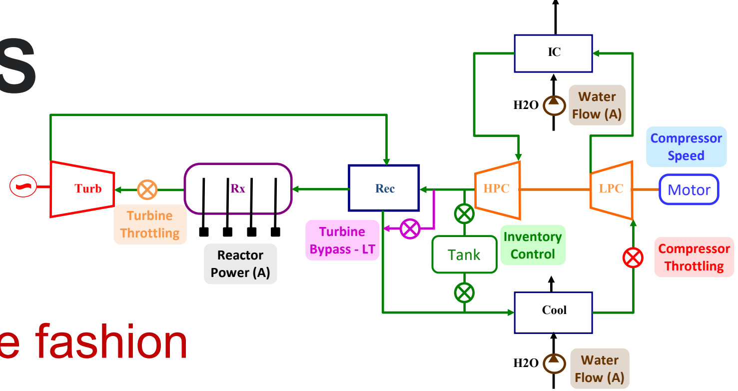
LOAD FOLLOWING BY INDIVIDUAL CONTROLS

INDIVIDUAL CONTROLS

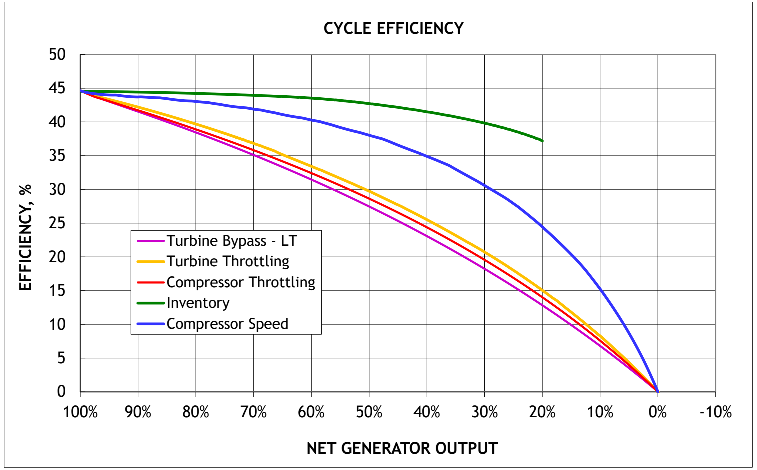
- Test if each control can meet load following goals
  - From 100% to 0% at 10%/min rate
    - Down transient only at this stage
  - Code input: grid demand
- One control at a time
  - Corresponding code input
    - E.g., shaft speed for compressor speed control
- Output: net generator output
  - Goal: match grid demand
- Limits
  - Compressor surge (stall)
  - Turbine/compressor choke
  - Lost of external controllability
    - E.g., reactor power goes to 0

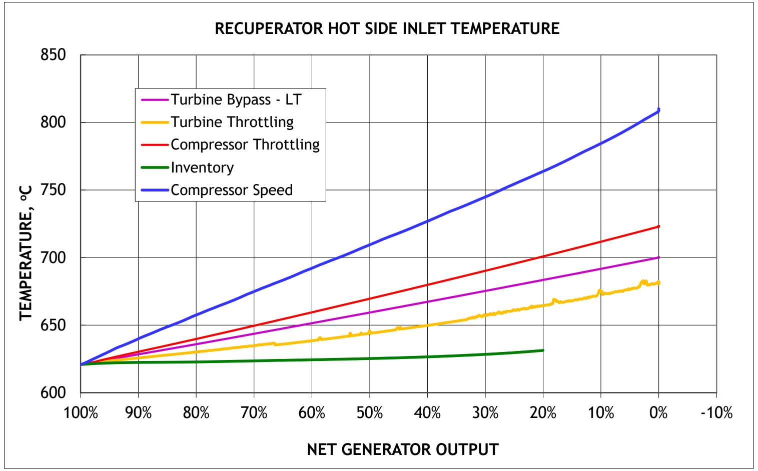
Time, s	Load, %
0	100
60	90
120	80
180	70
240	60
300	50
360	40
420	30
480	20
540	10
600	0
900	0

COMPARISON OF CONTROLS



- Collect the results from previous simulations
- All results are for 10%/min rate load following
  - Transient results presented in a steady-state fashion



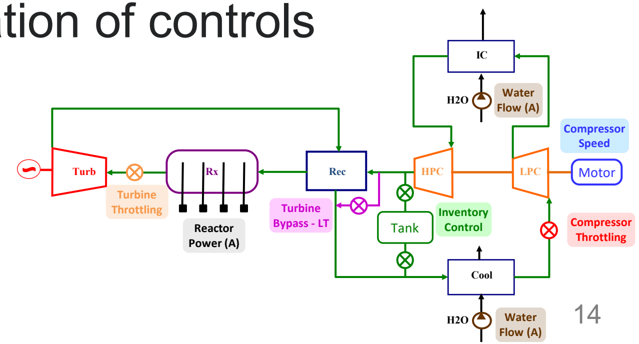


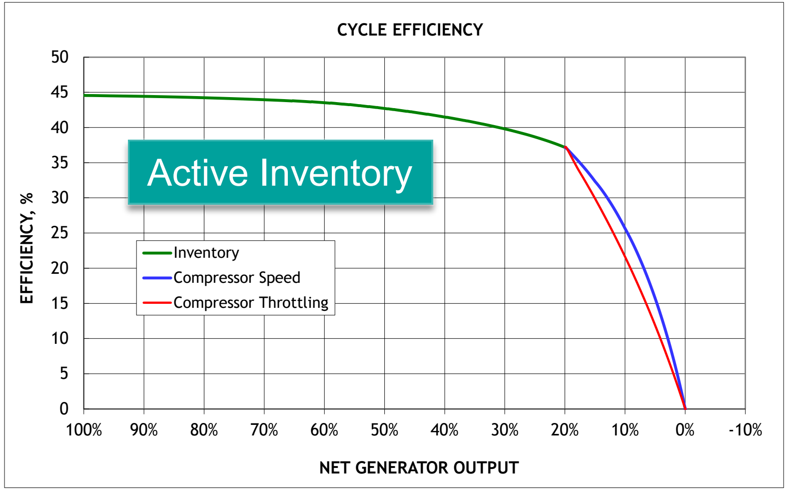
- Benefits of Inventory control: highest efficiency, little temperature variation
- Significant temperature increase for Compressor Speed control

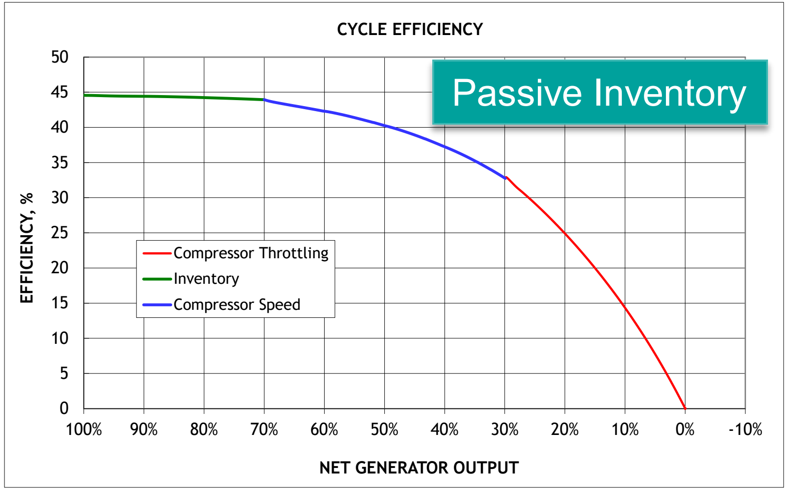
CONTROL STRATEGY

CONTROL STRATEGY

- Selecting best control mechanisms
  - For load following
  - Based on previous results
- Combination of controls
  - No one single control can do it all
- Two options:
  - With active inventory control – **preferred**
  - With passive inventory control
- New transient calculations
  - Combination of controls



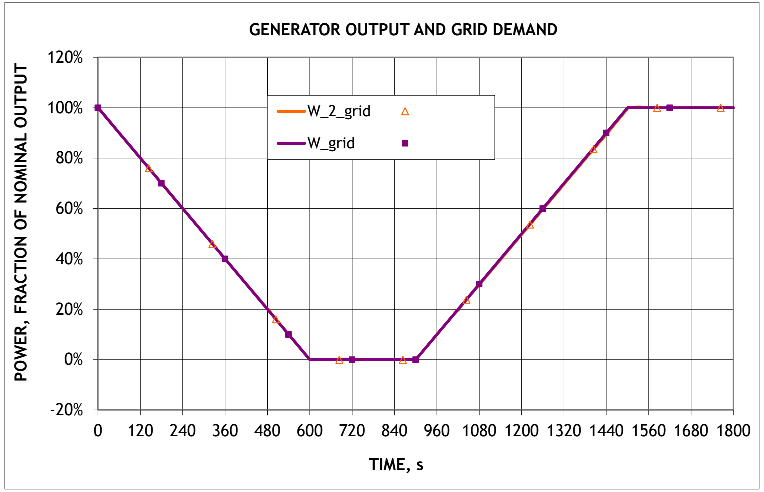


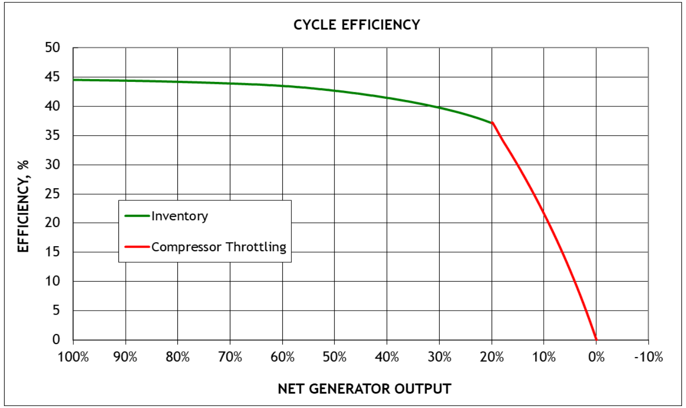


LOAD FOLLOWING DEMONSTRATION

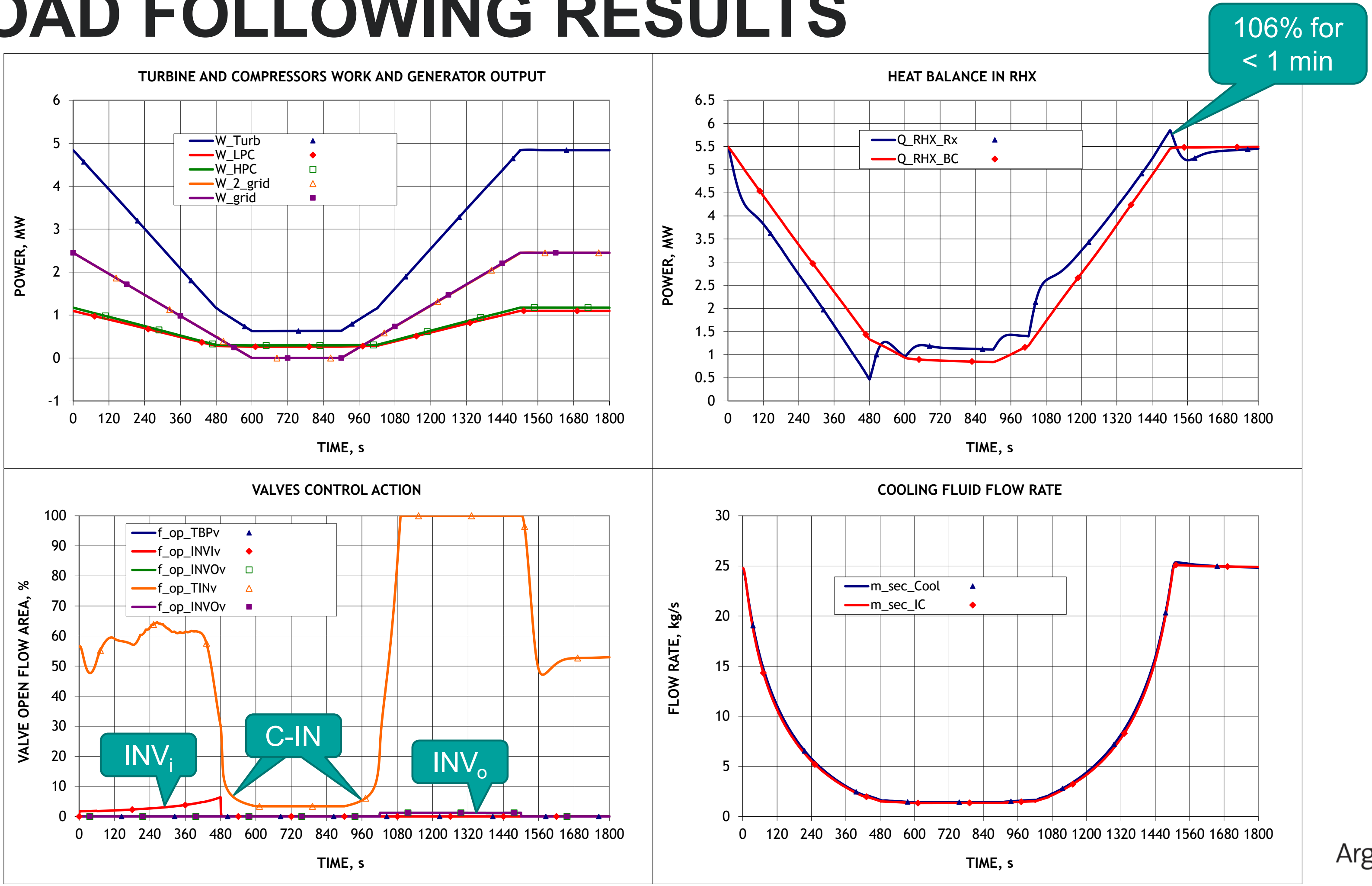
LOAD FOLLOWING

- Demonstrate Holos-Quad plant load following
- Over full range of loads
- From 100% to 0% and back to 100%
  - “Down and Up” transient
- Both ramps: 10%/min
  - Over 10 min = 600 s
- 5 min wait time at 0% and 100%
  - 300 s
- Entire transient: 30 min
- Results for Control strategy A – active inventory
  - Some differences for Option B

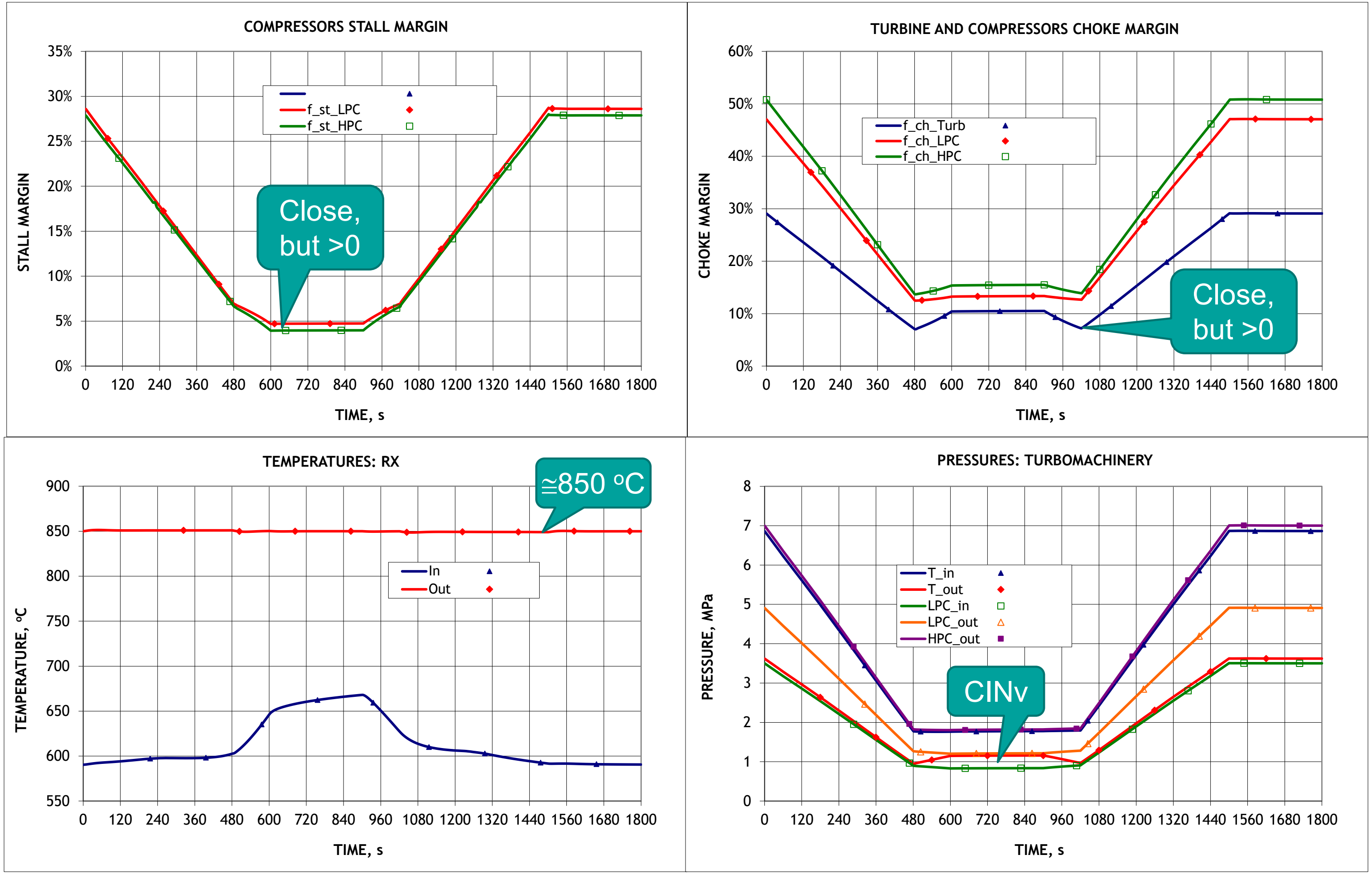




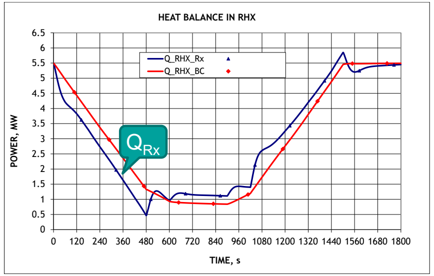
LOAD FOLLOWING RESULTS

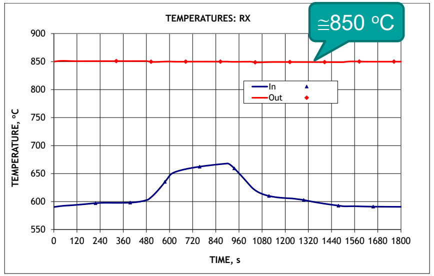


LOAD FOLLOWING RESULTS

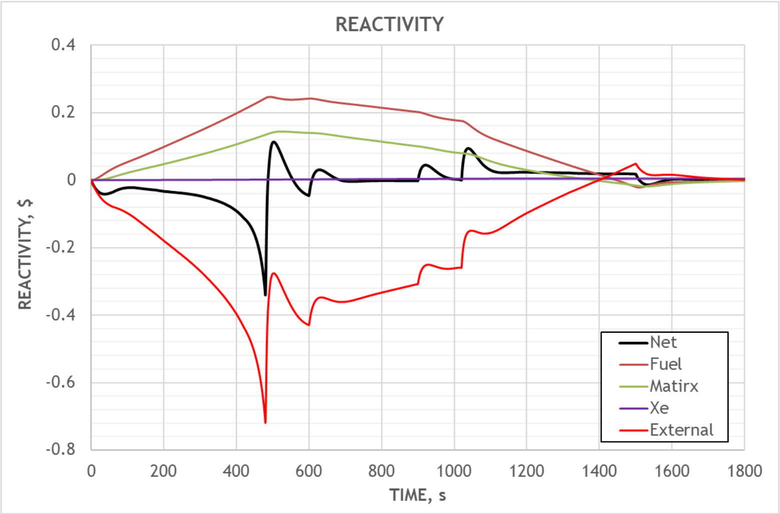


REACTOR CONTROL





- Presented analysis assumed that required power level will be achieved
  - To match heat demand from the Brayton cycle
  - And maintain Rx-outlet temperature
- From that power history, net reactivity is calculated
  - Using reactor kinetics equations
  - With delayed neutrons, decay heat, and reactivity feedbacks
  - The rest should come from control
- This external (control rod) reactivity was compared to the Holos-Quad control mechanisms (drums) capabilities
  - Found to be within design



Argonne NATIONAL LABORATORY

SUMMARY

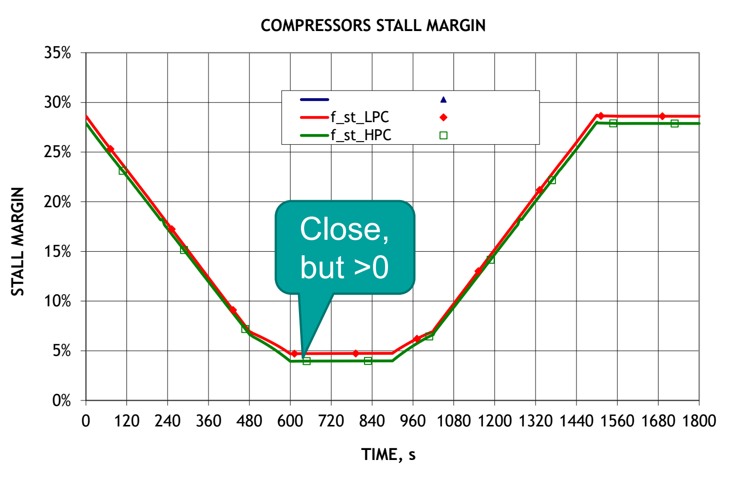
SUMMARY

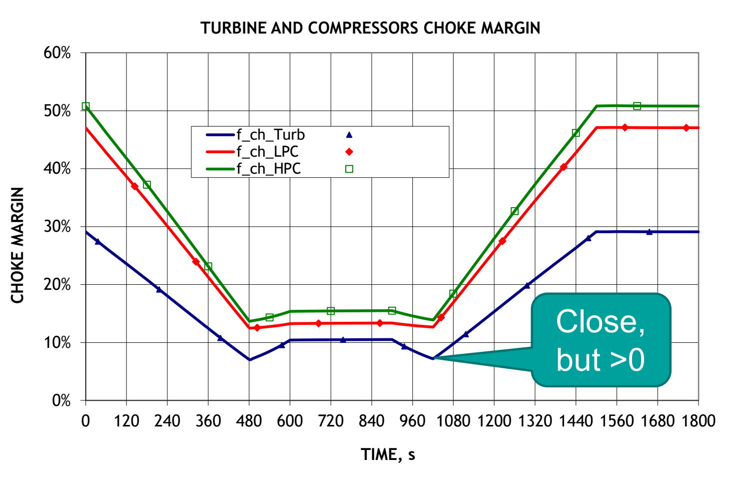
- Flexible operation of Holos-Quad micro-reactor was demonstrated
  - Using Plant Dynamics Code
- Brayton cycle control mechanisms identified and investigated
  - All options
- Load following
  - Grid demand changing between 100% and 0% at 10%/min rate
- Best option: inventory control
  - Limited by tank volume or reactor power
- Control strategy was developed
  - Combination of controls
  - Options for active or passive inventory control
  - Reactor and other components are characterized

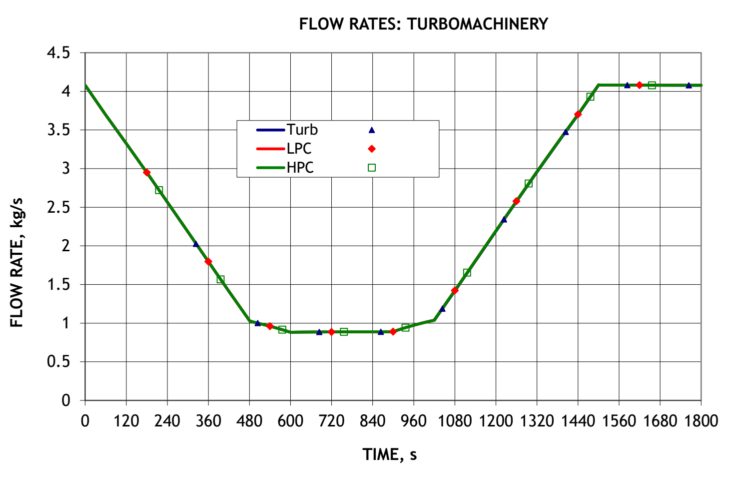
QUESTIONS?

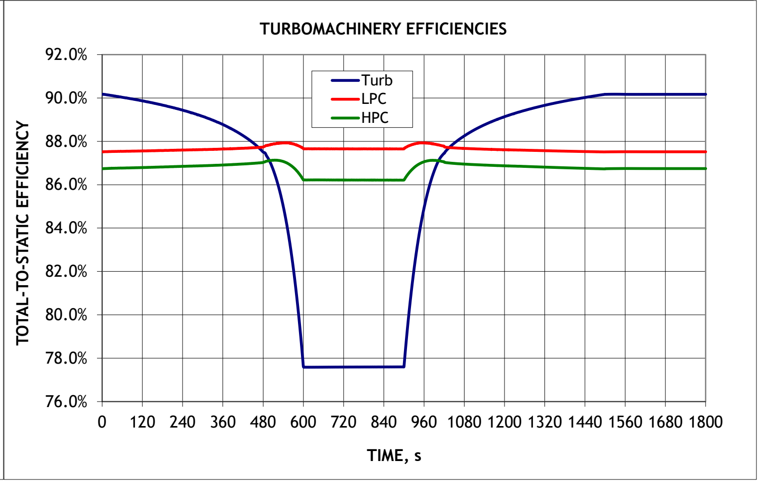
BACKUP: MORE LF RESULTS

LOAD FOLLOWING RESULTS

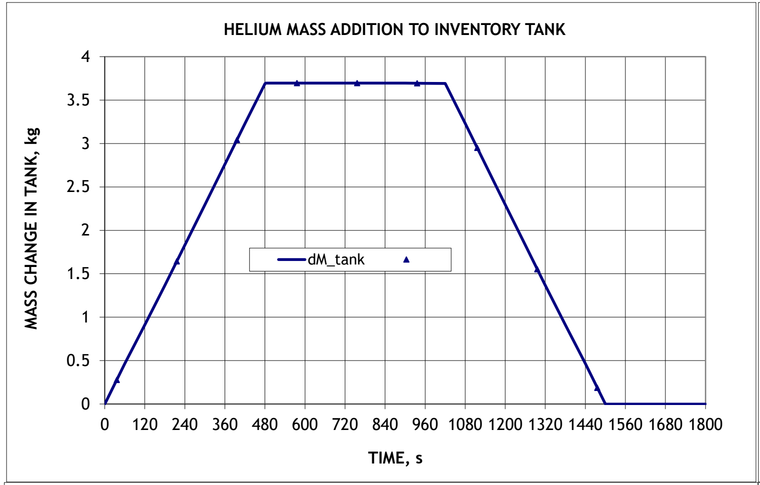


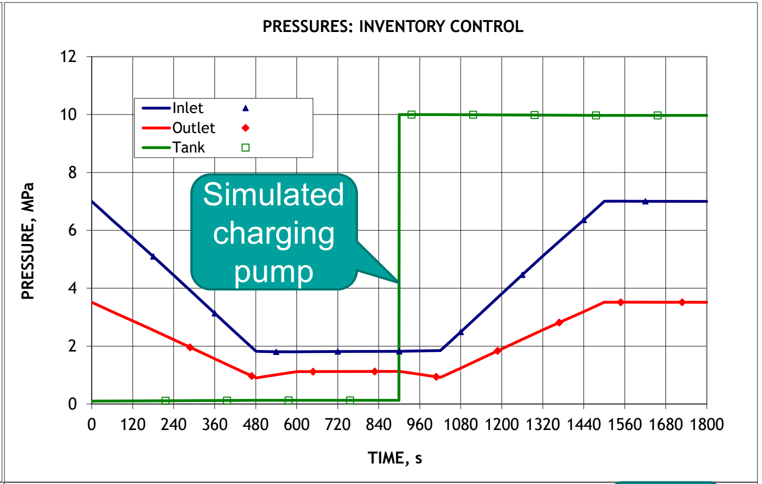


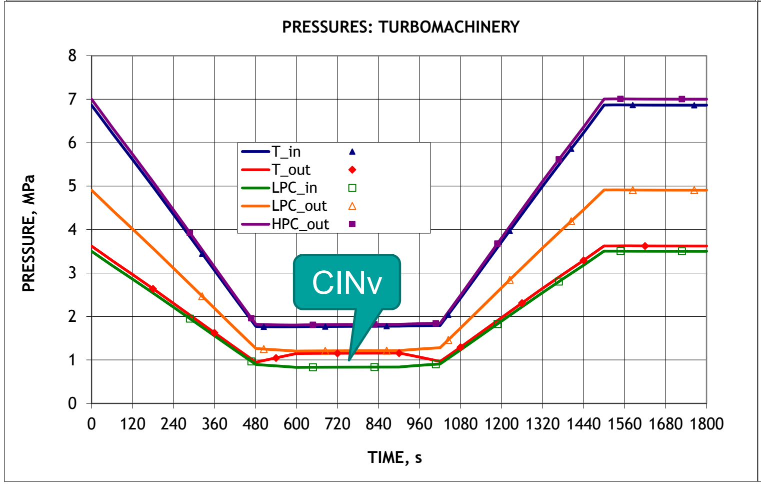


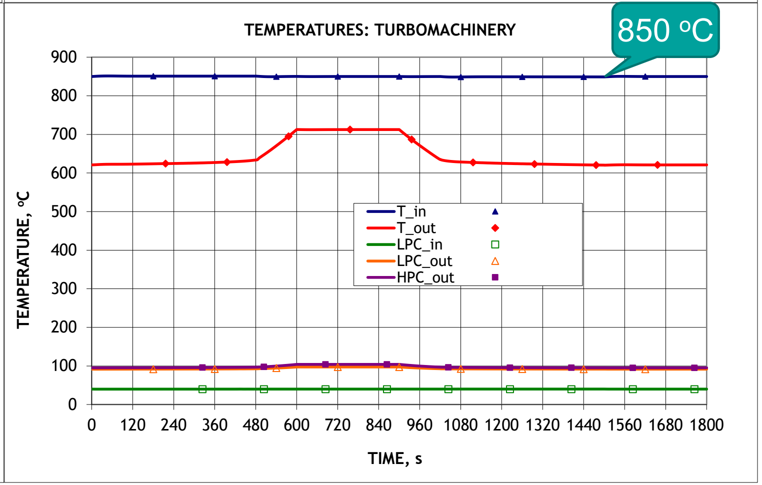


LOAD FOLLOWING RESULTS

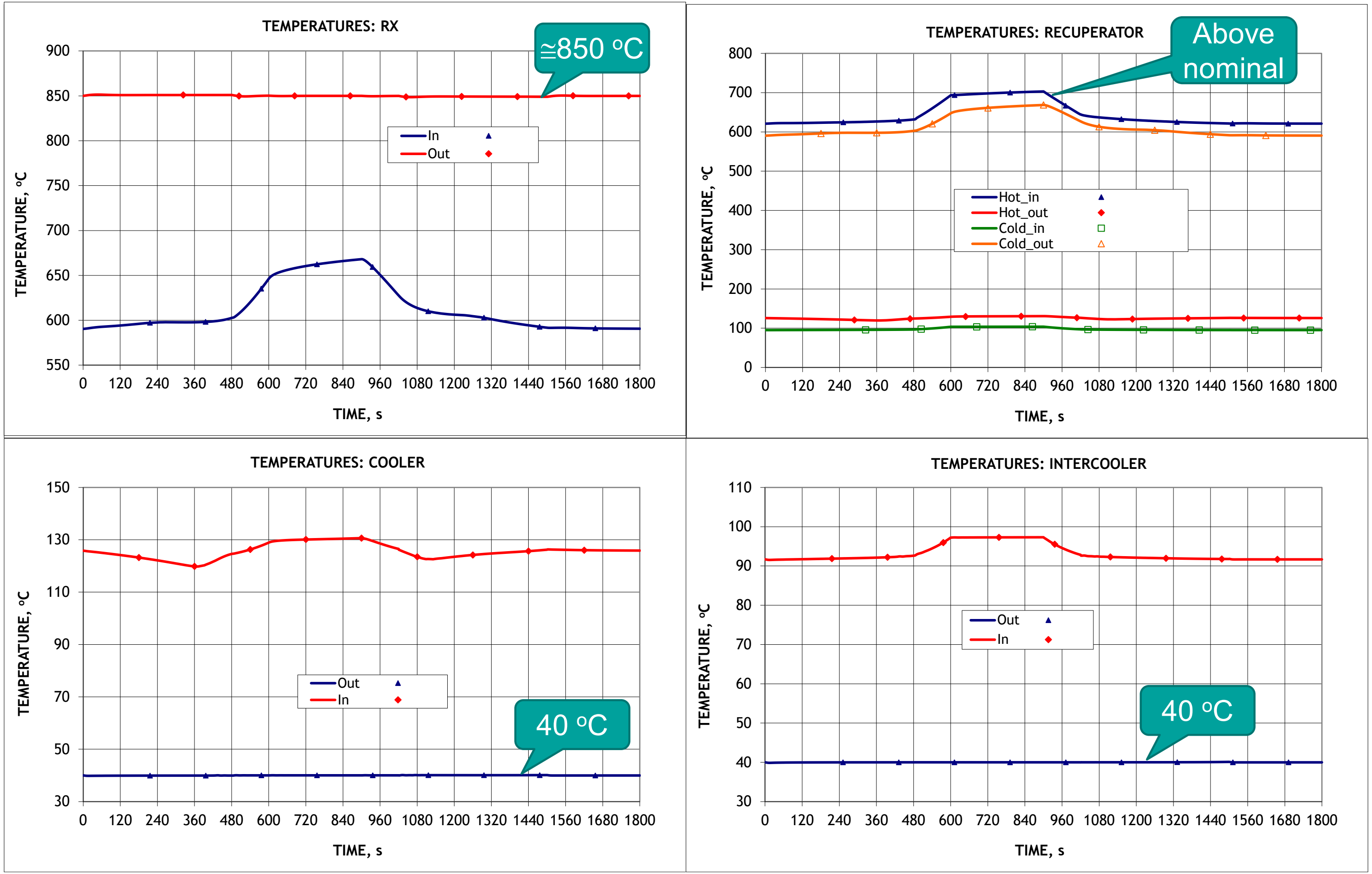






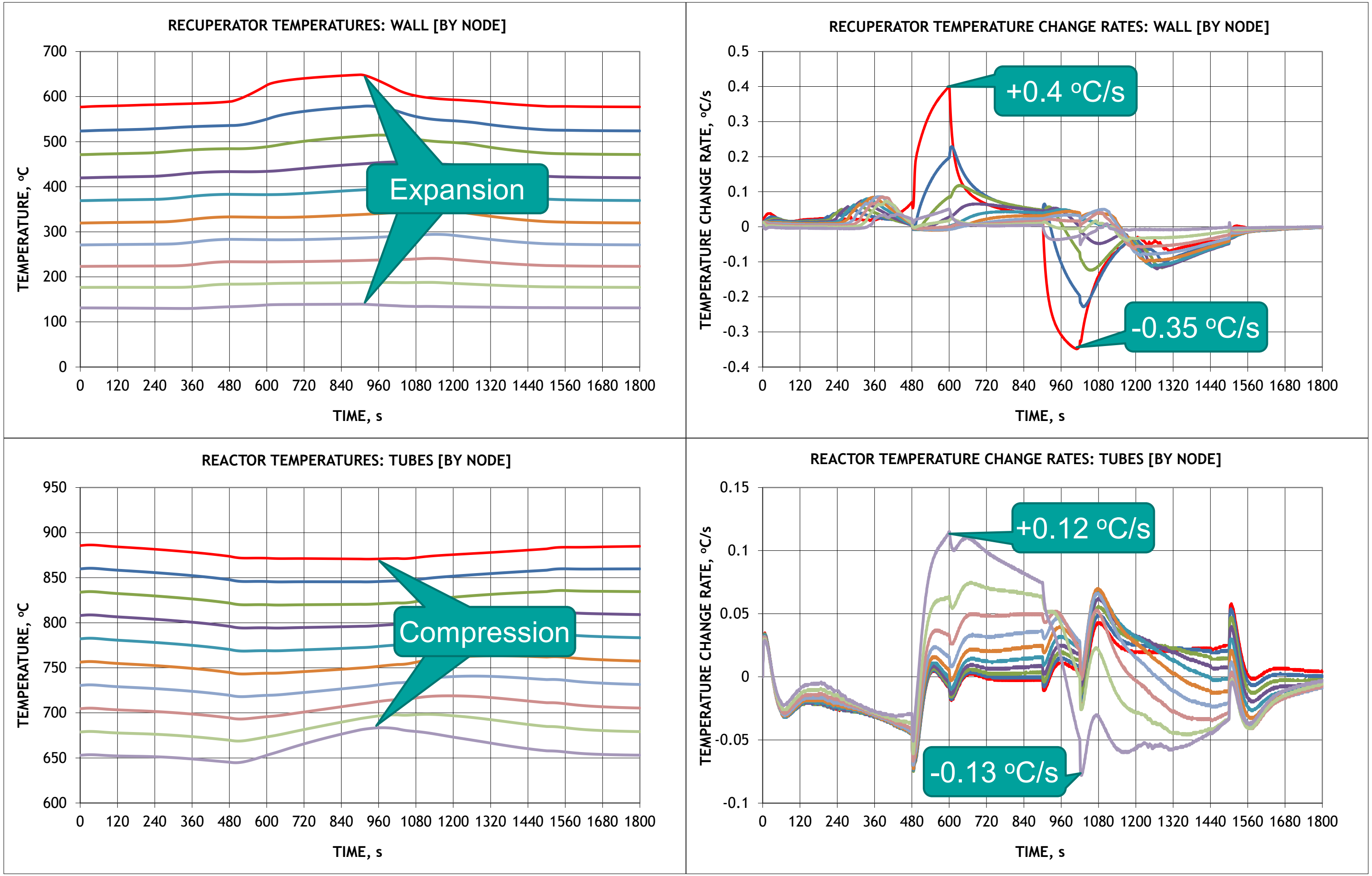


LOAD FOLLOWING RESULTS



Argonne NATIONAL LABORATORY

LOAD FOLLOWING RESULTS



Argonne NATIONAL LABORATORY

LOAD FOLLOWING RESULTS