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NATIONAL ENERGY TECHNOLOGY LABORATORY

Dynamic Modeling and Control Strategies for Flexible Operation of a 10 MWe Supercritical CO_2 Recompression Closed Brayton Cycle

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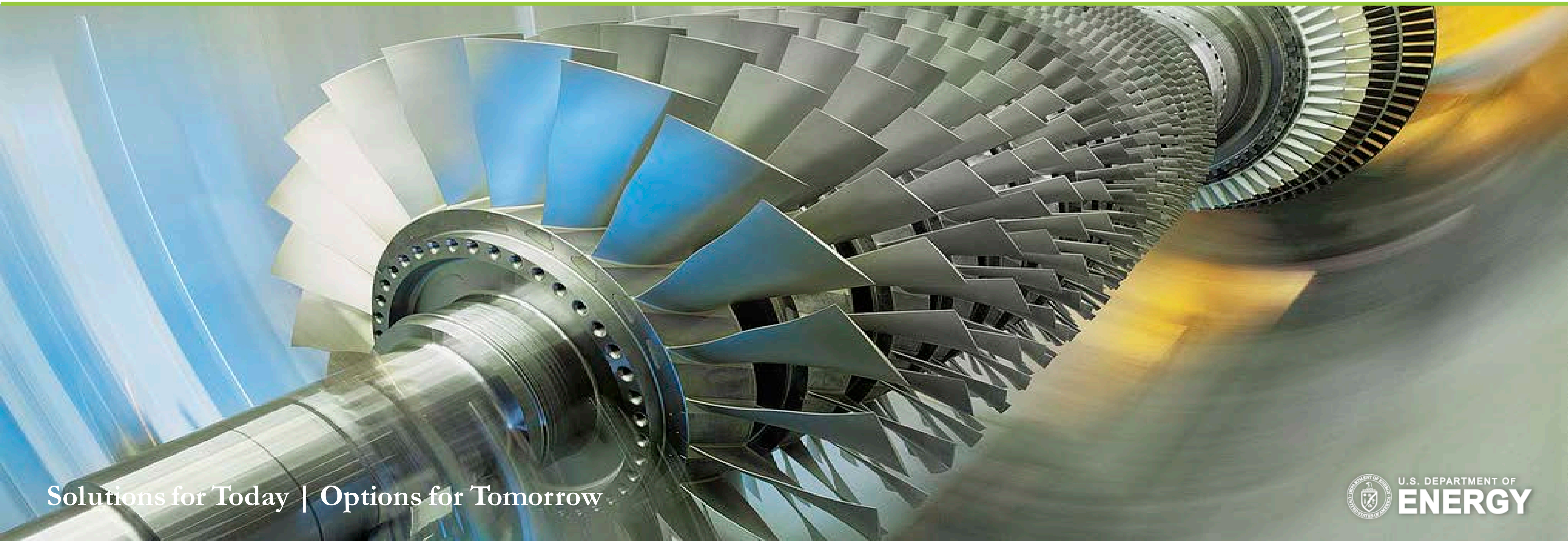
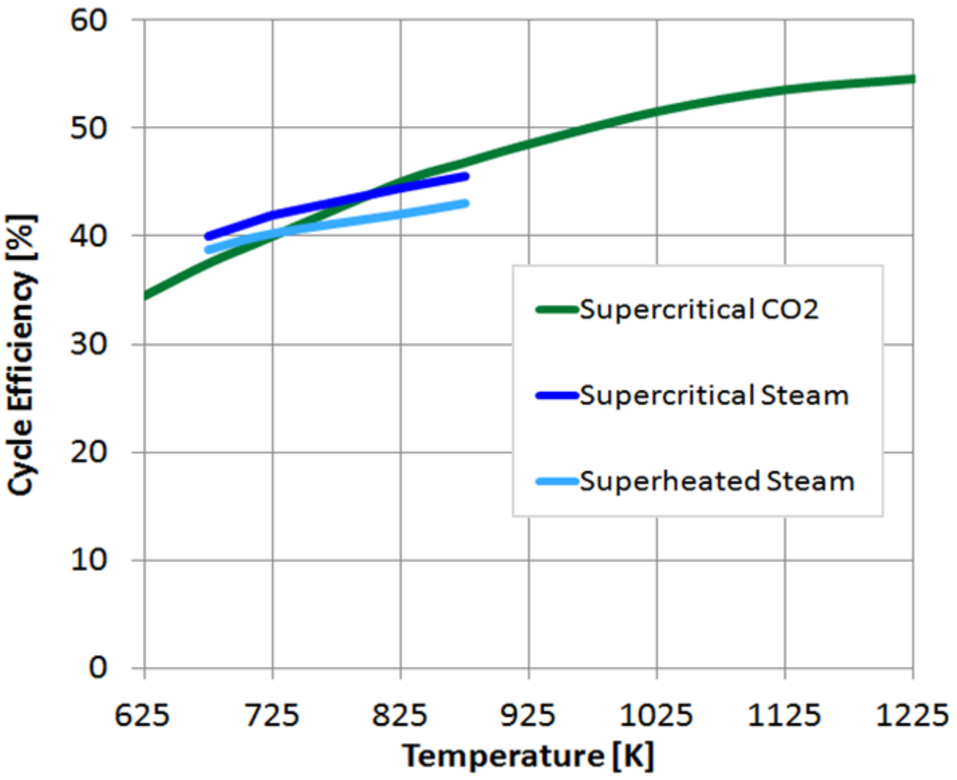


Motivation

Supercritical CO_2 (sCO_2) Brayton Power Cycles

- **Potential for higher efficiencies than traditional steam Rankine cycles**
- **Unique properties for sCO_2 working fluid**
  - Moderate conditions for supercritical state
    - Temperature: 304.2 K, Pressure 7.4 MPa
  - Liquid-like densities around the cycle
  - High density and low pressure ratio
    - Reduces compressor power requirements
    - Reduces size of turbomachinery by ~10X
  - Increased heat capacity near critical point
    - Enhances heat recuperation
- **Offers potential for flexible operations**



Motivation
U.S. DOE STEP Program: 10 MWe sCO_2 Pilot Plant

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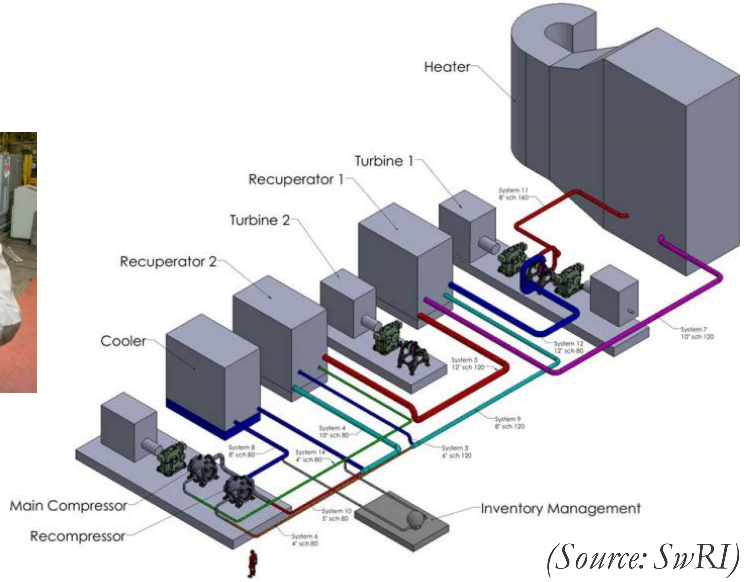
- **U.S. DOE's Supercritical Transformational Electric Power (STEP) Program**
- **sCO_2 Pilot Plant Test Facility**
  - Team led by: gti, SwRI Southwest Research Institute, GE + Wisconsin University of Wisconsin–Madison, Natural Resources Canada
  - Plan, design, build, and operate indirect-fired 10 MWe sCO_2 Brayton power cycle
    - Simple Cycle: TIT=500 °C
    - Recompression Cycle: TIT = 700-715 °C
  - Verify performance of key components
    - Turbomachinery, heat exchangers, …
  - Demonstrate cycle design, integration, operability, and controls (startup, transients)

(Source: GE)

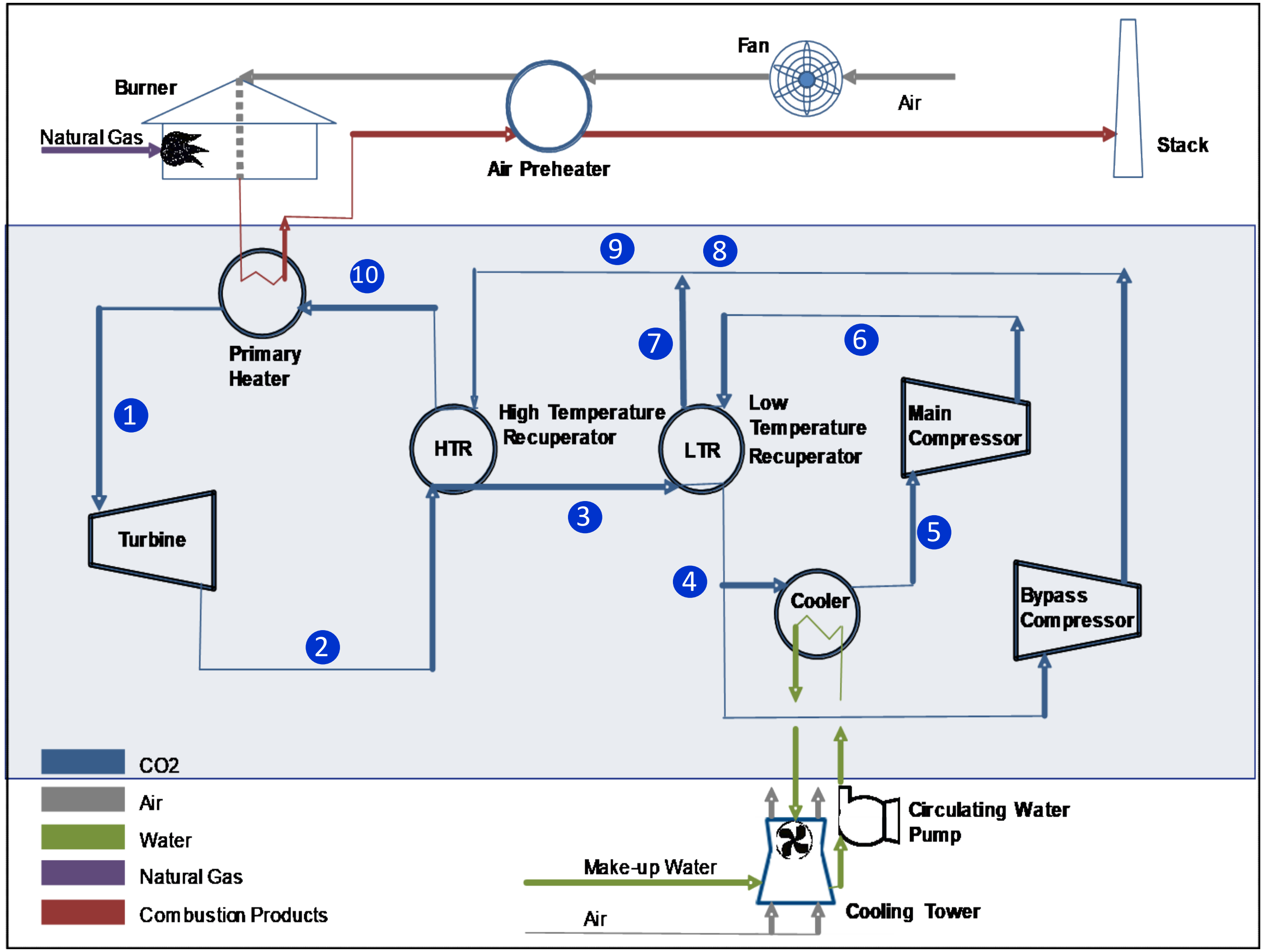


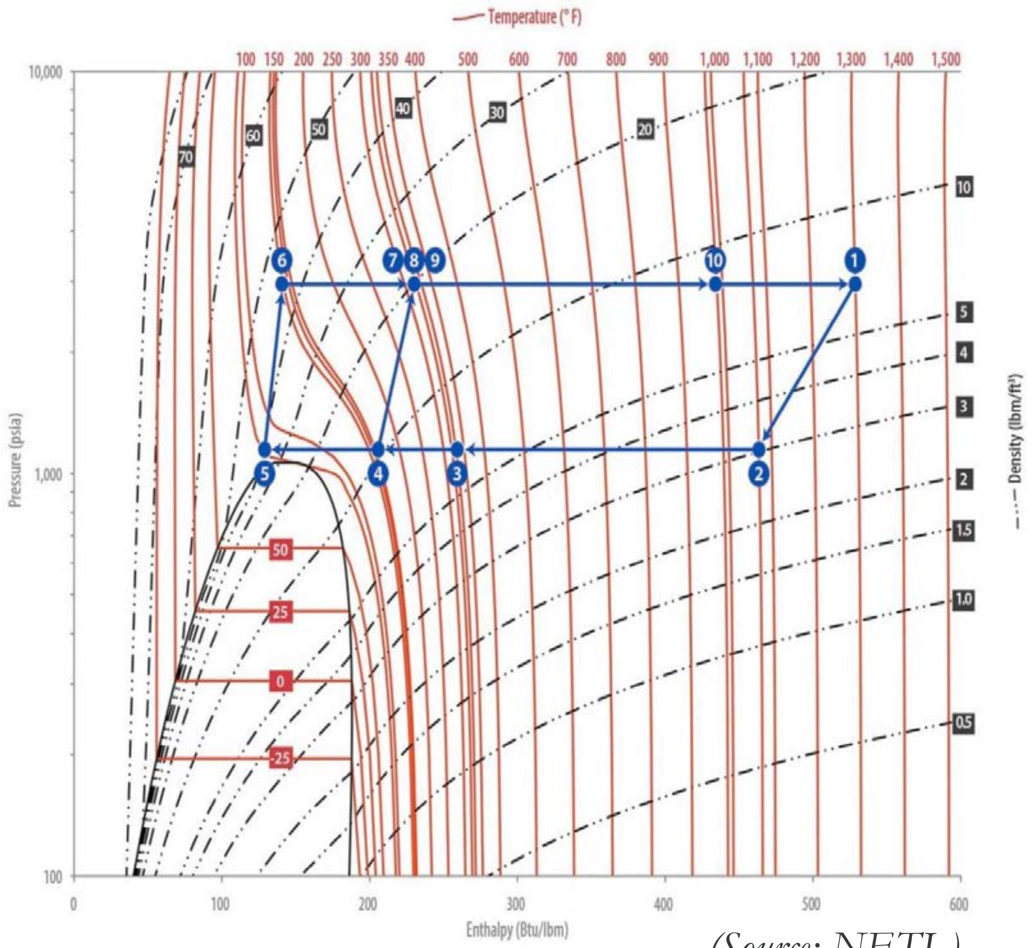
(Source: SwRI)

Presentation Overview

- sCO_2 Recompression Brayton Cycle Overview and Dynamic Modeling
- Regulatory Controls for Maximizing Efficiency
- Transient Results for Load-Following Operation
- Concluding Remarks and Ongoing/Future Work

sCO_2 Recompression Brayton Pilot Plant
Process Overview





(Source: NETL)

sCO_2 Recompression Brayton Pilot Plant
Dynamic Modeling

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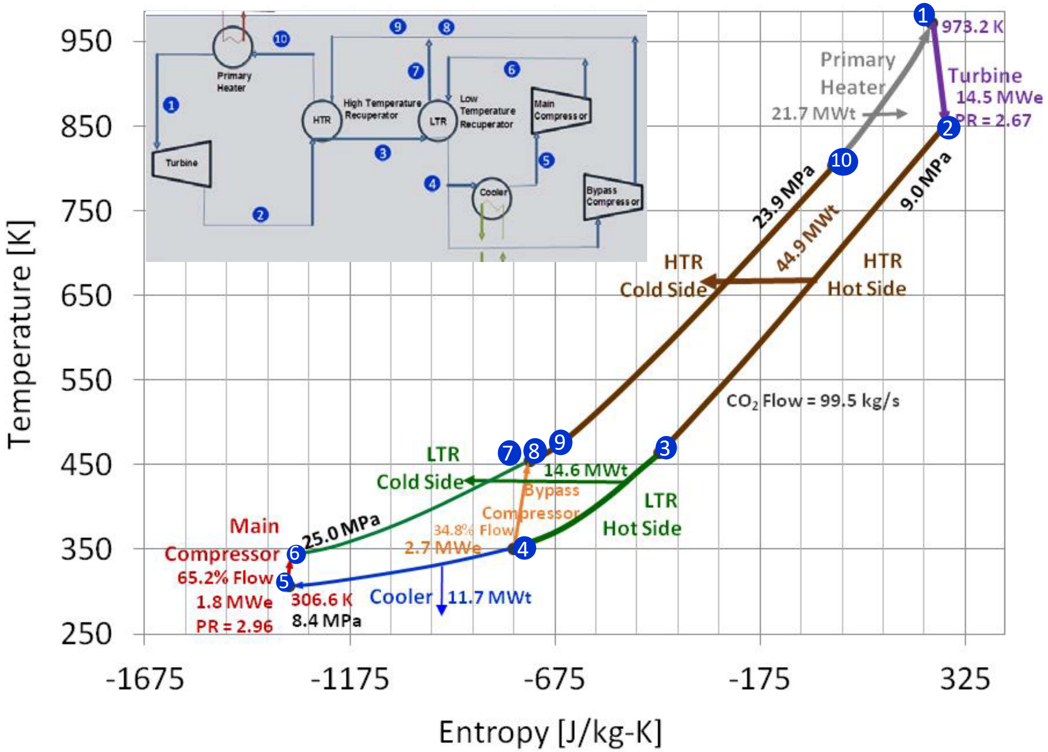
- **Software**
  - Aspen Plus Dynamics
- **Properties**
  - NIST REFPROP†
- **Dynamic Equipment Models**
  - Heat Exchangers
    - Shell-and-tube, countercurrent flow
    - Volume, ΔP, metal mass, heat transfer
  - Turbomachinery
    - Isentropic expansion/compression
    - Performance and efficiency curves
  - Piping††
    - Volume, ΔP, and heat transfer

- **Dynamic Results at Full Load (10MWe)**
  - Heat Input = 21.7 MWt, Efficiency = 46.1%
  - HTR+LTR Duty = 59.5 MWt, BC Flow Split = 34.8%
  - TIT = 973.2 K, Turbine Pressure Ratio = 2.67



† Span, and Wagner, W., "A New Equation of State for Carbon Dioxide Covering the Fluid Region from the Triple-Point Temperature to 1100K at Pressures up to 800 MPa," J. Phys. Chem. Ref. Data, 1996, 25(6), 1509-1596.

†† SwRI, Conceptual Design for a Supercritical Carbon Dioxide Power Cycle Test Facility, Volume II: Project Scope Plan, August 12, 2016.

sCO_2 Recompression Brayton Pilot Plant
Control Architecture – Maximize Efficiency

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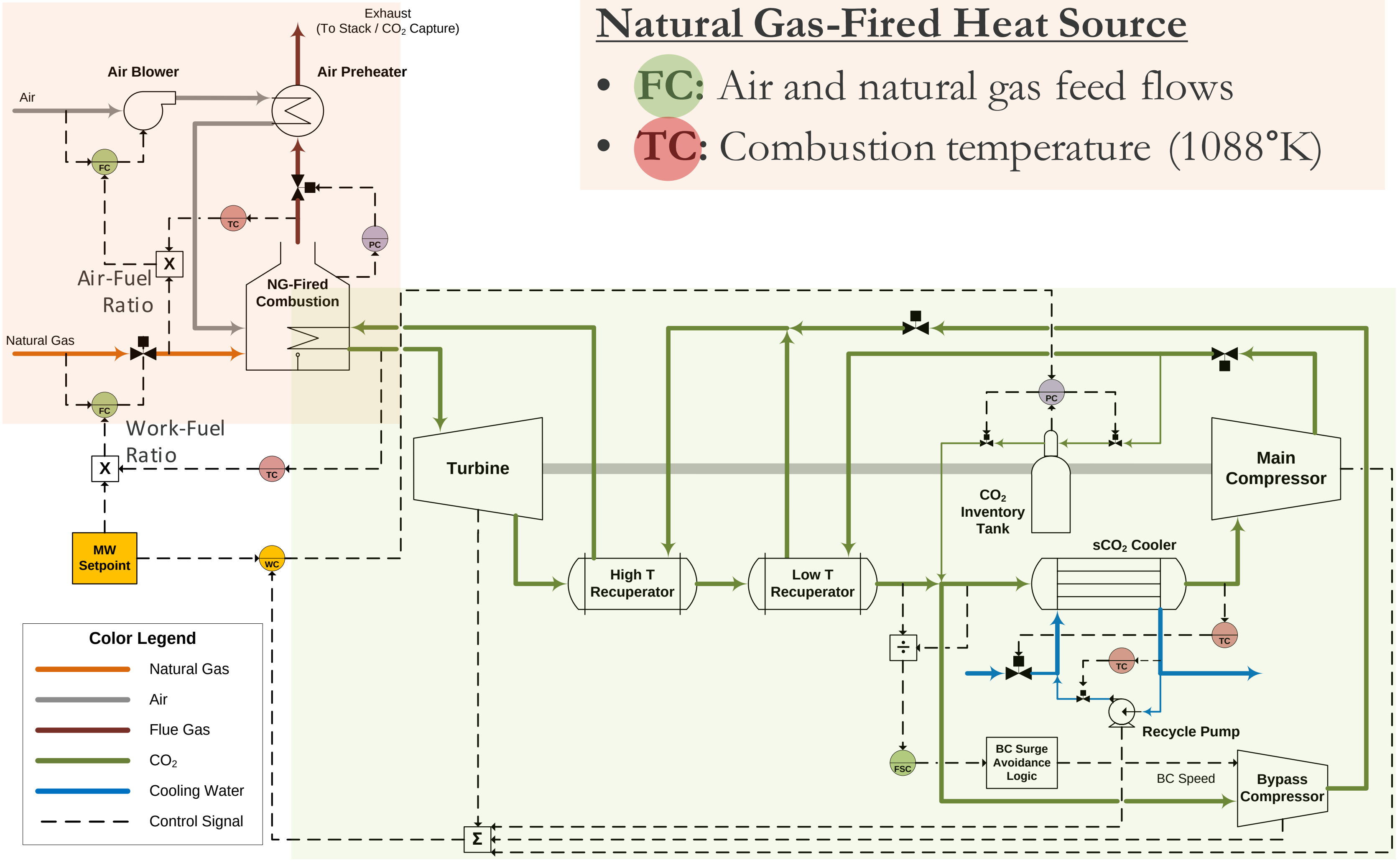

Natural Gas-Fired Heat Source

- **FC**: Air and natural gas feed flows
- **TC**: Combustion temperature (1088°K)

sCO2 Brayton Cycle

- **WC**: Load demand (net work)
- **TC** : Turbine inlet temperature
  - 973°K, with UB of 988°K
- **PC**: Inventory tank pressure
- **TC**: MC inlet temperature
  - 306.5°K, with LB of 304.1°K
- **TC**: CW exit temperature
  - Upper bound of 323°K
- **FSC**: Flow split (BC vs. MC)
  - Design: 0.348
  - Bypass compressor surge margin ≥ 10%

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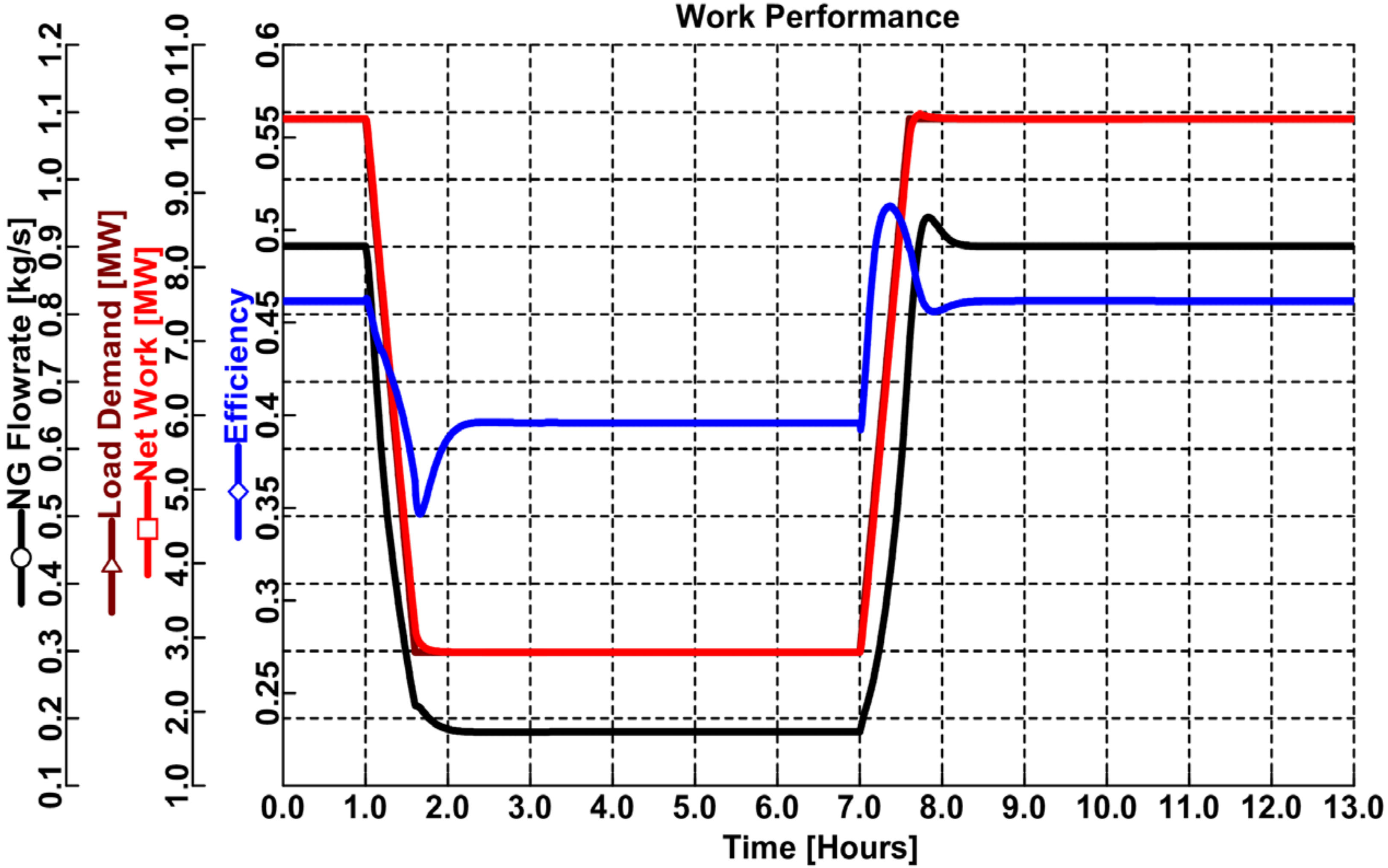
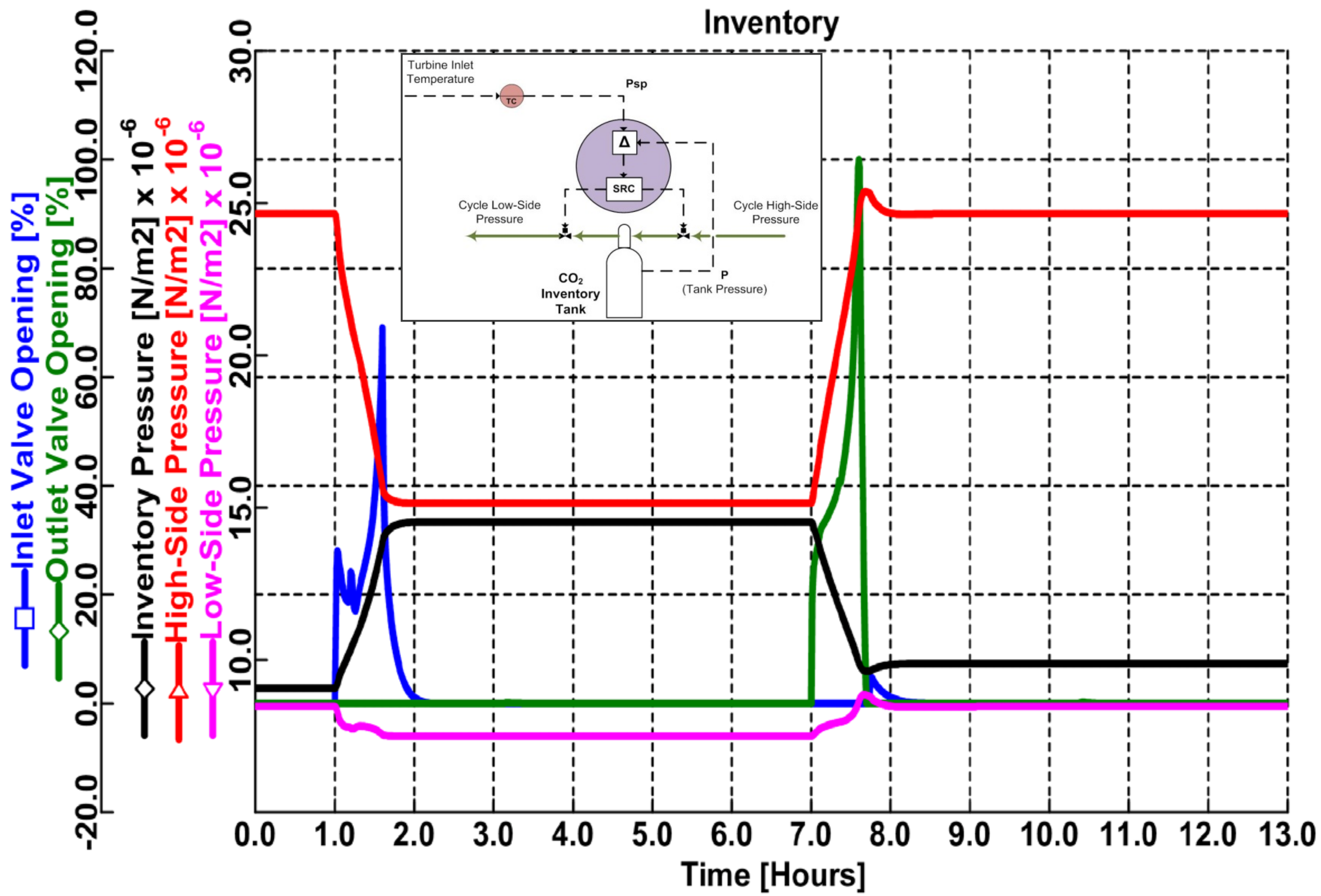
Load-Following Results

Ramp Down from Full-Load (10 MWe) to 28% Load (2.8 MWe) and Ramp Back Up to Full-Load



- **Load demand** ramped down over a period 0.6 hr (2%/min)
- During ramp-down, **NG flowrate** is reduced and sCO_2 is rapidly removed from the cycle into the inventory tank (Opposite for ramp up)
- 28% load is minimum load at which TIT can be kept at its design value (973°K)
- **Efficiency** drops from 46% to 40% after ramp down
- Ramp back up to full-load at t = 7 hr using same ramp rate
- **Actual net-work** closely follows the **load demand** with no visible lag

Load-Following Results
Inventory Control and Sliding Pressure Operation



Ramp Down

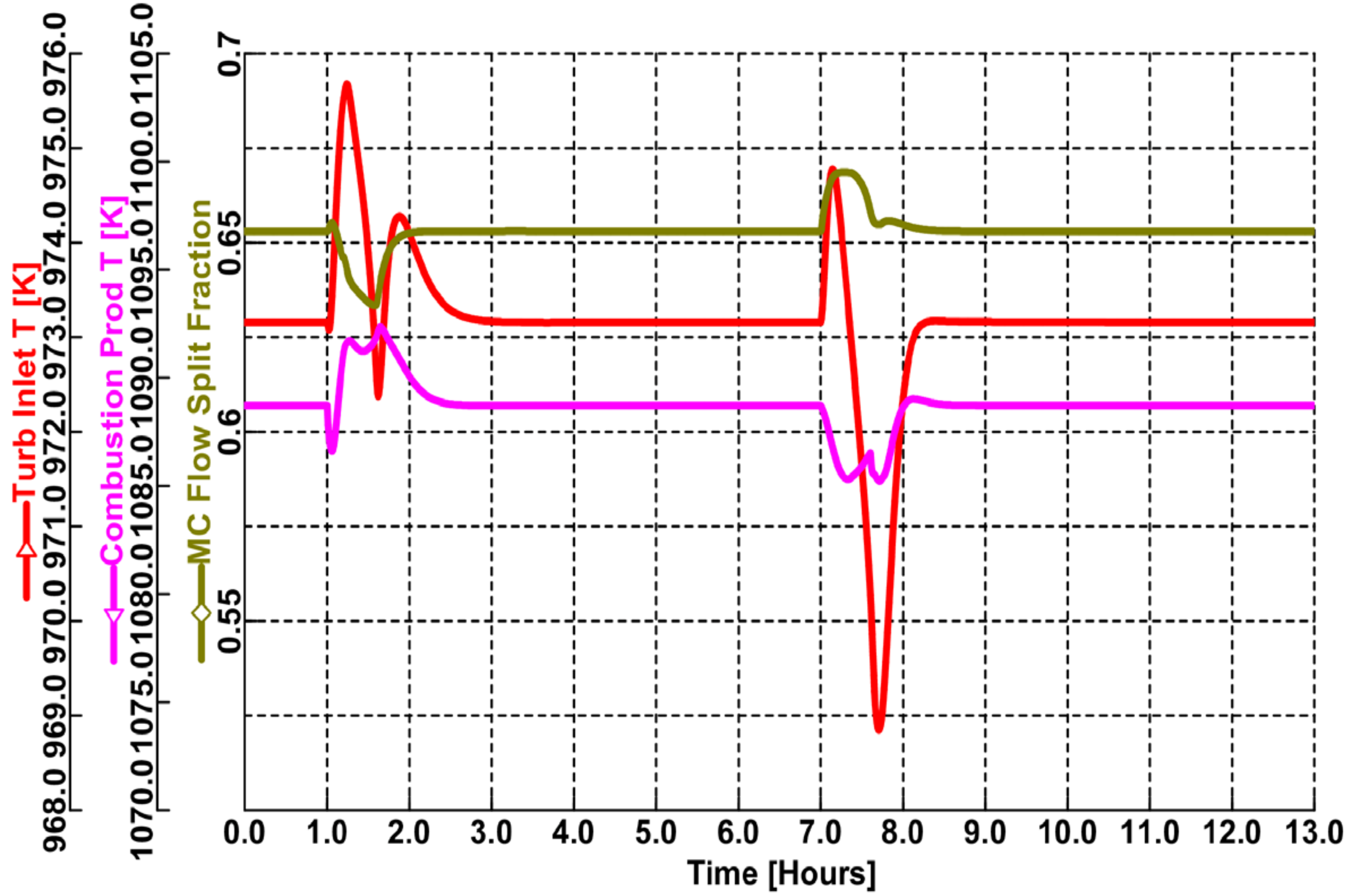
- sCO_2 cycle **high-side pressure** and **low-side pressure** slide down
- sCO_2 is diverted into inventory tank by opening **inlet valve**
- Inventory **tank pressure** increases

Ramp Up

- sCO_2 is put back into cycle by opening **outlet valve**, thereby reducing **tank pressure**
- Split-range controller logic ensures that both valves are never open at the same time, thereby avoiding continuous sCO_2 flow across the tank

Load-Following Results

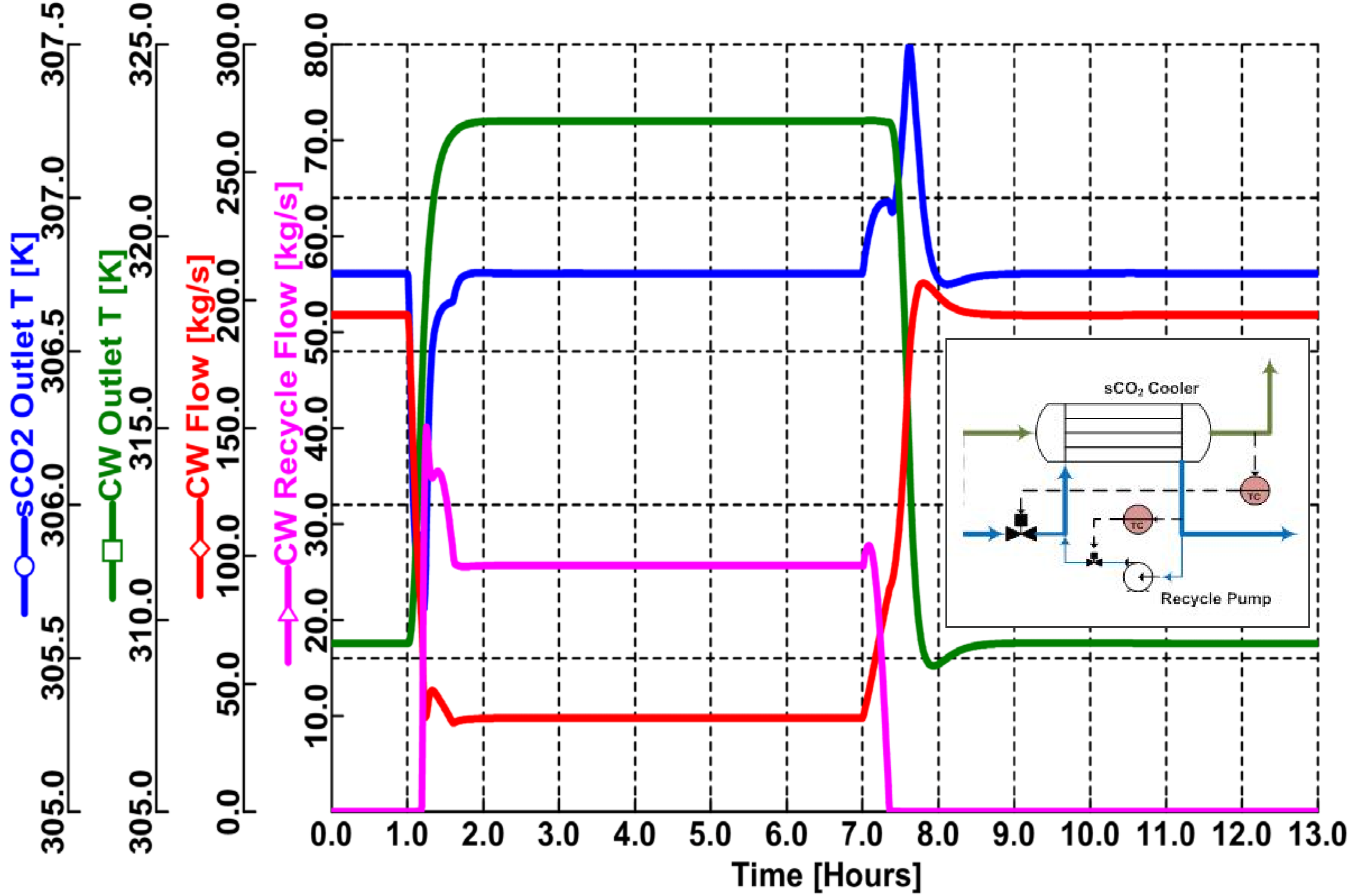
Turbine Inlet Temperature (TIT) Control



- **TIT** remains within 5°K of design (973°K) and well below UB of 988°K
- **Combustion temperature** is well controlled in the NG furnace which serves as the indirect heat source to the sCO_2 cycle
- **Flow split** between BC and MC is also well controlled

Load-Following Results

sCO_2 MCIT and Cooling Water Temperature Control



Ramp Down

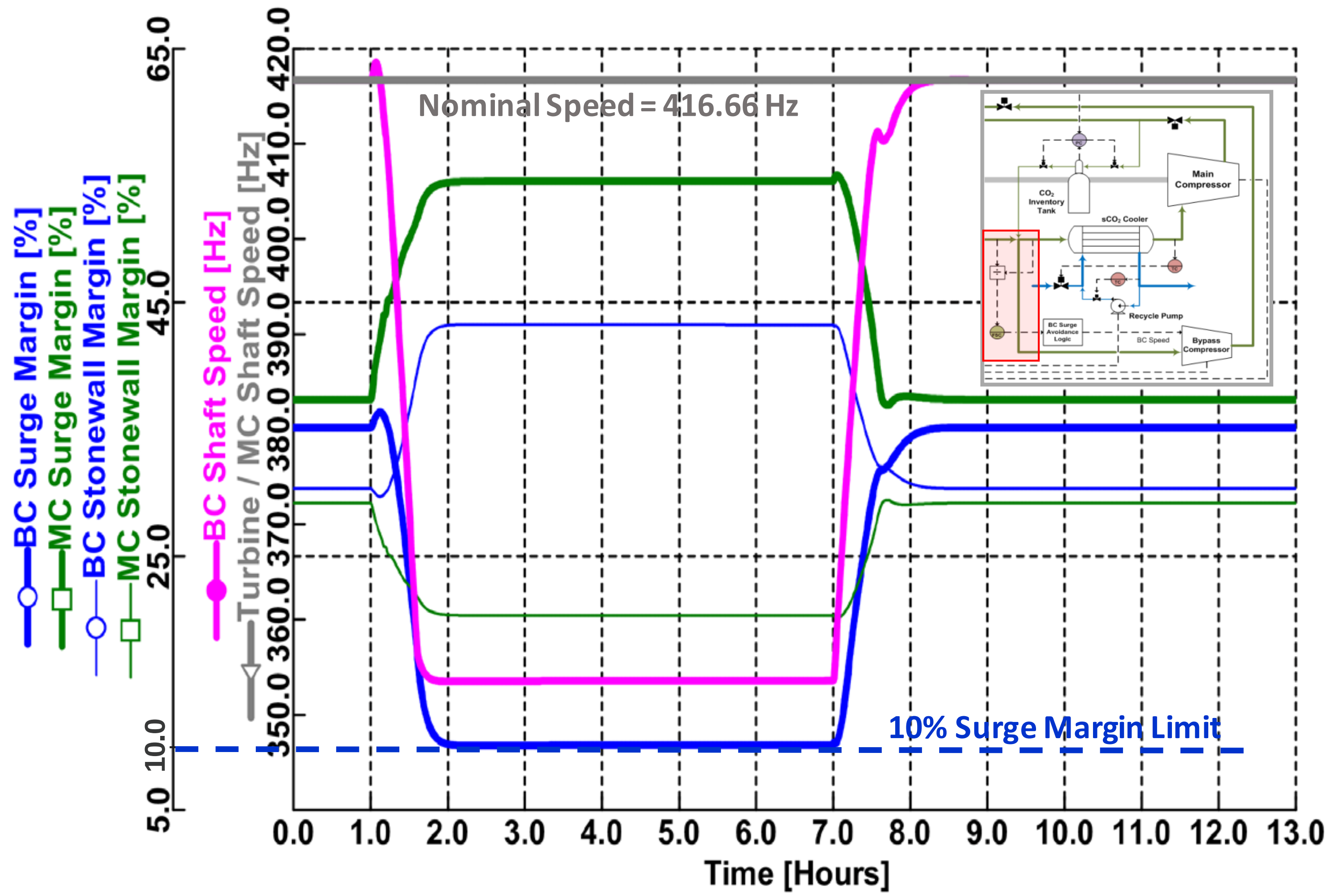
- **CW flow** decreases, keeping **sCO_2 MCIT** > LB of 304.1°K ($T_{Critical}$)
- **CW outlet temperature** rapidly rises during turndown
- **CW recycle starts** to keep the **CW outlet temperature** at its UB of 323°K

Ramp Down/Up

- **MCIT** is well controlled with a net variation of 1°K

Load-Following Results

Flow-Split Control: Compressor Speeds and Surge Margins



Ramp Down

- Using **flow-split-control (FSC)**, the **BC shaft-speed** is reduced to maintain the design sCO_2 flow split at its design value
- More flow goes through the MC, increasing the **MC surge margin**
- **BC surge margin** moves very close to constraint of 10%

Comments

- FSC using varying **BC shaft-speed** adds operational complexity
- **BC surge margin** becomes a factor at low loads, requiring the need for surge control

Concluding Remarks

- **Developed pressure-driven dynamic model of a 10MWe sCO_2 recompression Brayton pilot plant**
- **Developed regulatory controls for maximizing efficiency of load-following operations**
  - Sliding-pressure operation via inventory control used to maintain TIT
  - CW flow used to maintain sCO_2 MCIT above $T_{critical}$
  - Flow-split-control used to increase efficiency during load-following operation
- **Analyzed cycle performance and control for MW-demand turndown and subsequent ramp-up at a 2%/min ramp rate**
  - TIT is maintained at design (973°K) down to 28% load
  - Efficiency over 40% is maintained throughout turndown to 28% load
- **Further turndown is achievable using a combination of inventory, flow split, and flow-rate control, while letting the TIT drop below design value†**

† Zitney, S.E. and E.A. Liese, "Dynamic Modeling and Simulation of a 10 MWe Supercritical CO2 Recompression Closed Brayton Power Cycle for Off-Design, Part-Load, and Control Analysis," Proceedings of the 6th International Supercritical CO2 Power Cycles Symposium, Pittsburgh, PA, March 27-29 (2018).

Ongoing and Future Work

10MWe sCO_2 Recompression Brayton Cycle

- **Dynamic Modeling and Control**
  - Compact heat exchanger for cooler and recuperators
  - Turbine controls and compressor surge control
  - Advanced process control, including model predictive control
- **Transient Operations**
  - Startup and shutdown
  - Safety analysis
- **Validation**
  - Exploit real-time data from STEP pilot plant test facility
  - Validate dynamic models and controls

Websites and Contact Information

Office of Fossil Energy: www.energy.gov/fe/office-fossil-energy

NETL: www.netl.doe.gov/

sCO_2 Technology
Program: www.netl.doe.gov/research/coal/energy-systems/sco2-technology

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