Dynamic Modeling and Simulation of a 10 MWe Supercritical CO_2 Recompression Closed Brayton Power Cycle for Off-Design, Part-Load, and Control Analysis

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6th International Supercritical CO_2 Power Cycles Symposium, Pittsburgh, PA, March 27–29, 2018

Presentation Overview

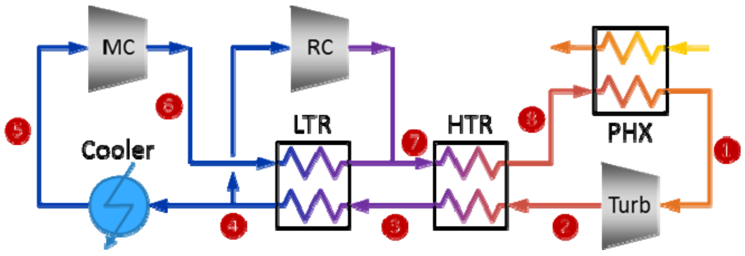
- **Introduction**
  - Supercritical CO_2 (sCO_2) Recompression Brayton Cycle
  - U.S. DOE's Supercritical Transformational Electric Power (STEP) Program
- **Modeling and Design**
  - 10 MWe sCO_2 Recompression Brayton Pilot Plant
  - Software Tools, Physical Properties, and Unit Operation Models
  - Steady-State Design
- **Transient Studies for Part-Load Operation (Heat Input Turndown)**
  - Operational/control strategies for maintaining cycle efficiency
    - Impact of CO_2 Storage Capacity and Pressure with Inventory Control
    - Impact of Flow Split and Flow Rate Control
- **Conclusions and Future Work**

Indirect sCO_2 Recompression Brayton Cycle

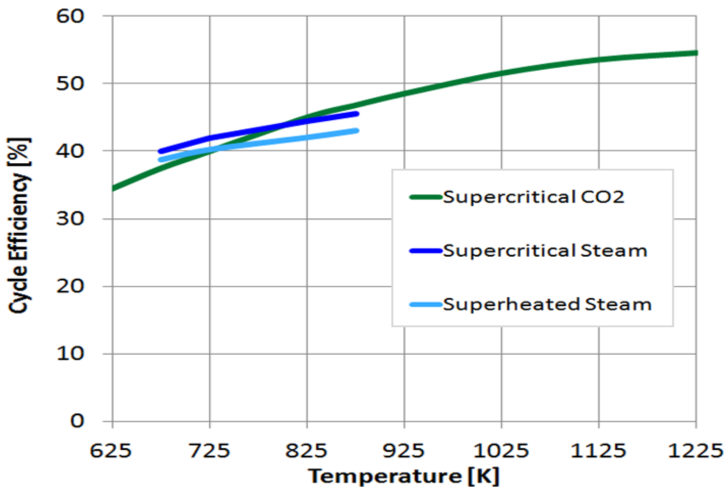
Benefits

- **Potential for higher efficiencies relative to traditional power cycles**
  - Reduced cycle compression power near the CO_2 critical point
  - Single phase fluid heat transfer
  - Extensive high-quality heat recuperation from turbine exhaust reduces cycle heat rejection
  - Bypass compressor (recompression) further enhances cycle recuperation and efficiency
- **Higher sCO_2 working fluid density and lower cycle pressure ratio**
  - Reduces size and cost of turbomachinery

Indirect sCO_2 Recompression Brayton Cycle

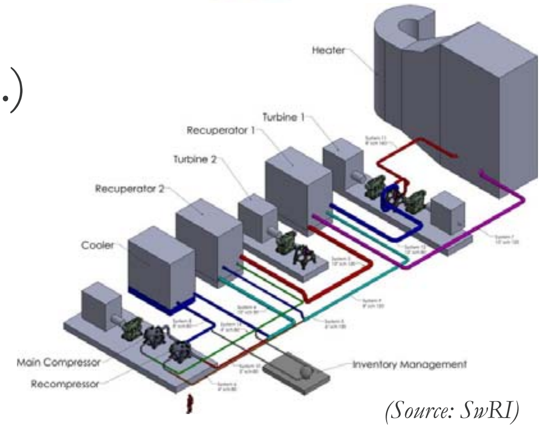


(Source: NETL)



U.S. DOE’s Supercritical Transformational Electric Power (STEP) Program

- **DOE crosscutting initiative to demonstrate supercritical CO_2 (sCO_2) Brayton power cycle technologies at commercial scale**
- **10 MWe sCO_2 Pilot Plant Test Facility**
  - Plan, design, build and operate an indirect sCO_2 recompression Brayton power cycle
  - Verify component performance (turbomachinery, recuperators, etc.)
  - Demonstrate potential for producing a lower COE and cycle efficiency approaching 50% or more
  - Demonstrate cycle integration, operability (steady-state, transient, load-following), instrumentation, and controls



(Source: SwRI)

http://energy.gov/under-secretary-science-and-energy/articles/doe-announces-80-million-investment-build-supercritical

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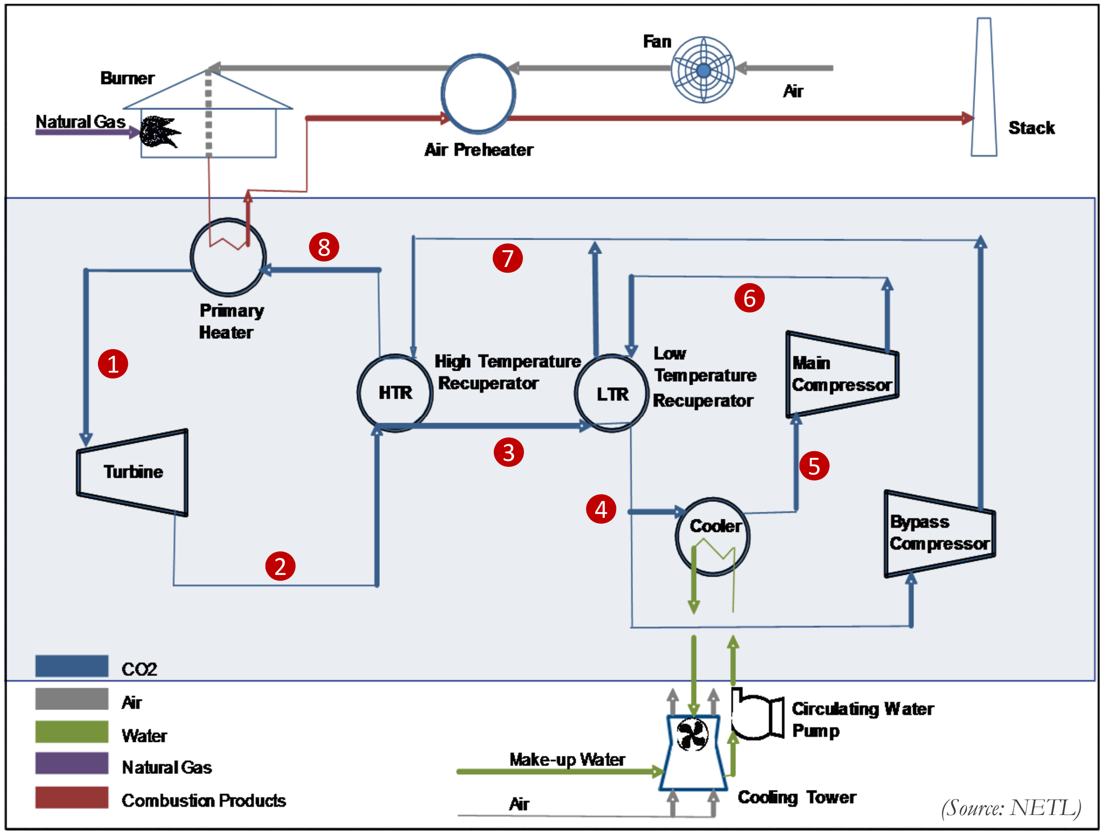
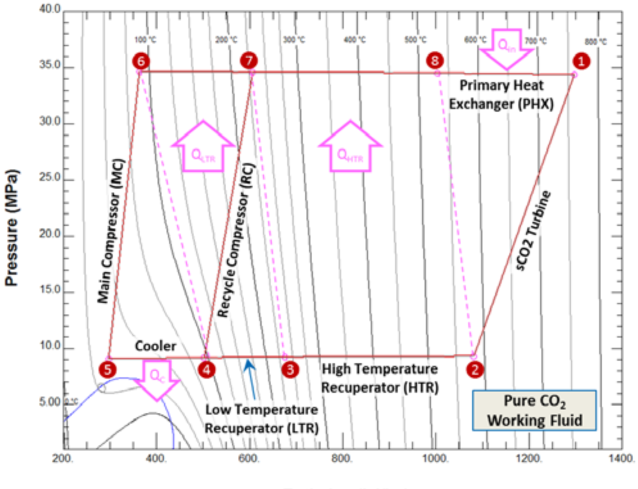
10 MWe sCO_2 Recompression Brayton Pilot Plant

Process Overview



(Source: NETL)

- External gas-fired heat source
- sCO_2 circulates in closed loop (noncondensing)
- Two stages of recuperation used to pre-heat compressed sCO_2 with hot turbine exhaust
- Cooler rejects heat that is not converted to power
- Parallel compressors, decoupled turbomachinery

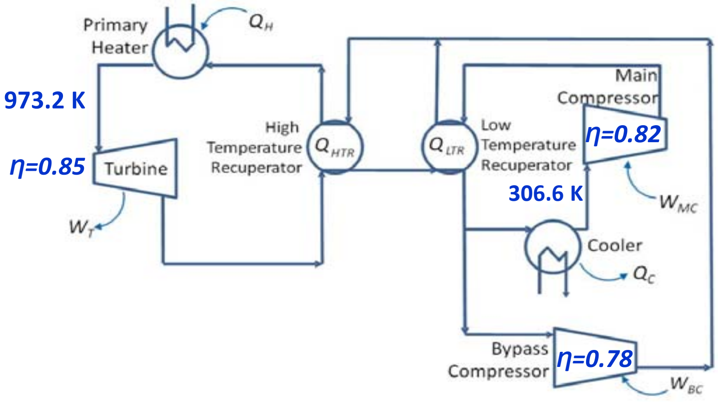


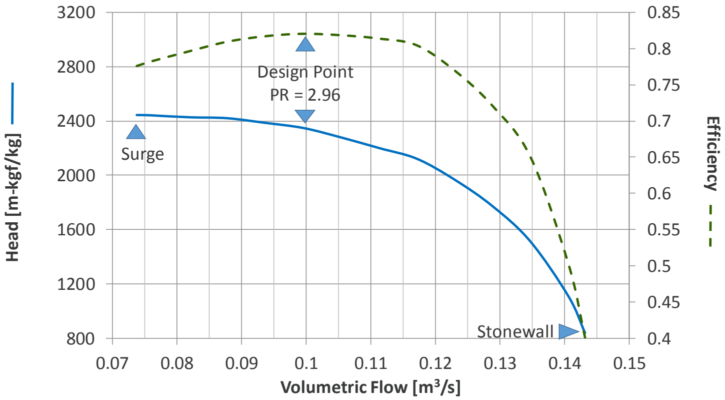
(Source: NETL)

sCO$_2$ Recompression Brayton Pilot Plant

Modeling: Software, Physical Properties, Unit Operations

- **Software Tools**
  - Aspen Plus/Dynamics v8.8
- **Property Method**
  - NIST REFPROP: EOS from Span and Wagner (1996)[†]
- **Unit Operation Models**
  - Heat Exchangers
    - Shell-and-tube, countercurrent flow
    - Dynamic Options/Specifications
      - Volume = (residence time)∗(steady-state volumetric flow rate)
      - Metal masses calculated using Aspen Exchanger Design and Rating
  - Turbomachinery
    - Single-stage, Isentropic
    - Dynamics: Performance/Efficiency Curves
      - Compressor curves scaled from data taken from CCSI(2014)[††]
      - Turbine curve scaled from data taken from Pasch et al.(2012) [†††]
      - Single curve at reference speed with fan laws used for varying speed
  - Piping
    - Length, inner diameter, and mass per unit length from SwRI (2016)[††††]





Performance and efficiency curves for Main Compressor

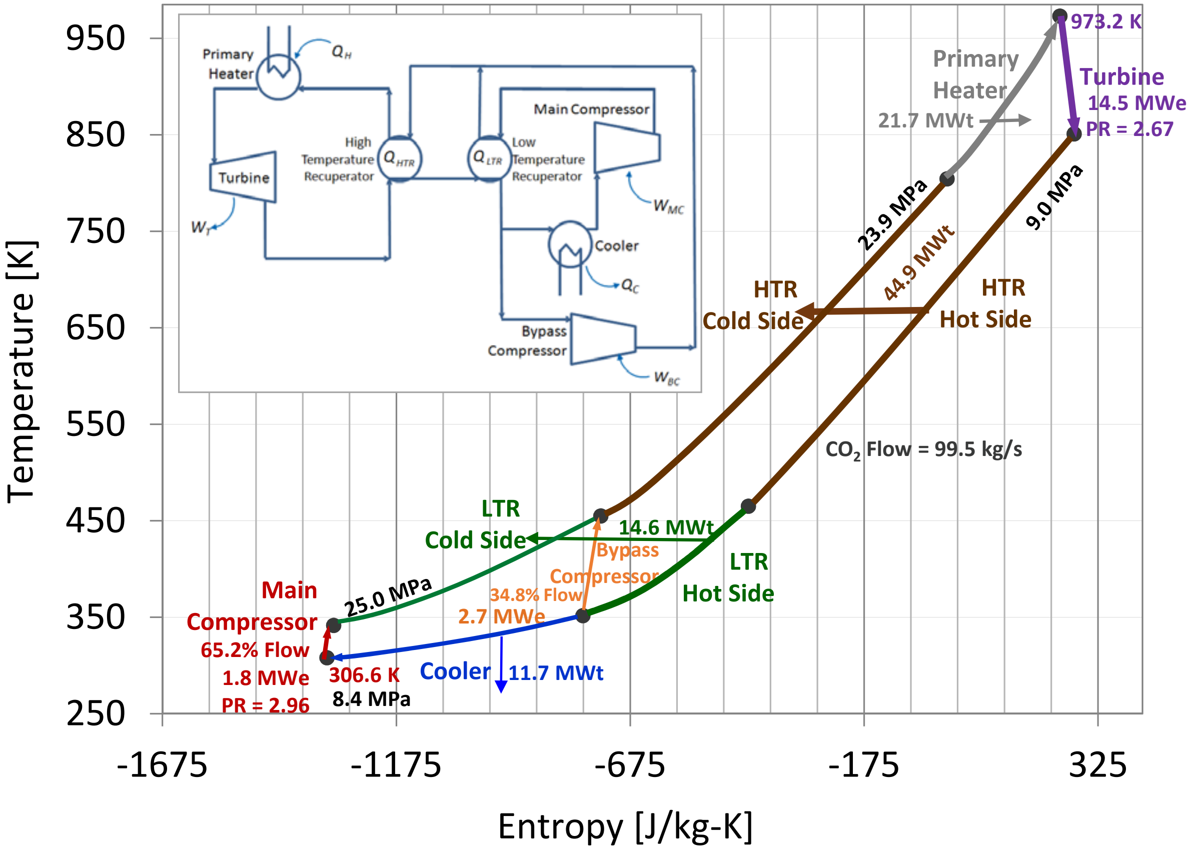
[†] Span, R. and Wagner, W., "A New Equation of State for Carbon Dioxide Covering the Fluid Region from the Triple-Point Temperature to 1100K at Pressures up to 800 MPa," J. Phys. Chem. Ref. Data, 1996, 25(6), 1509-1596.

[††] DOE/NETL Carbon Capture Simulation Initiative (CCSI) CO2 Compressor Simulation User Manual (2014)

[†††] Pasch et al., "Supercritical CO2 Recompression Brayton Cycle: Complete Assembly Description", SAND2012-9546, (2012).

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

10 MWe sCO_2 Recompression Brayton Cycle
Simulation Results: Steady-state Design Point



- Net power is 10 MWe.
  - $W_{NET} = W_T - W_{MC} - W_{BC}$
- Heat input is 21.7 MWt.
- Low pressure ratio (PR)
  - Turbine PR = 2.67 (23.9 MPa/ 9.0 MPa)
- Cycle is highly recuperated.
  - $(Q_{HTR}+Q_{LTR})/Q_H = 2.7$
  - $Q_{HTR}/Q_{LTR} = 3.1$
- Bypass compressor flow is ~1/3 of total CO_2 flow.
- Cooler rejects 11.7 MWt.
- Efficiency is 46.1%.

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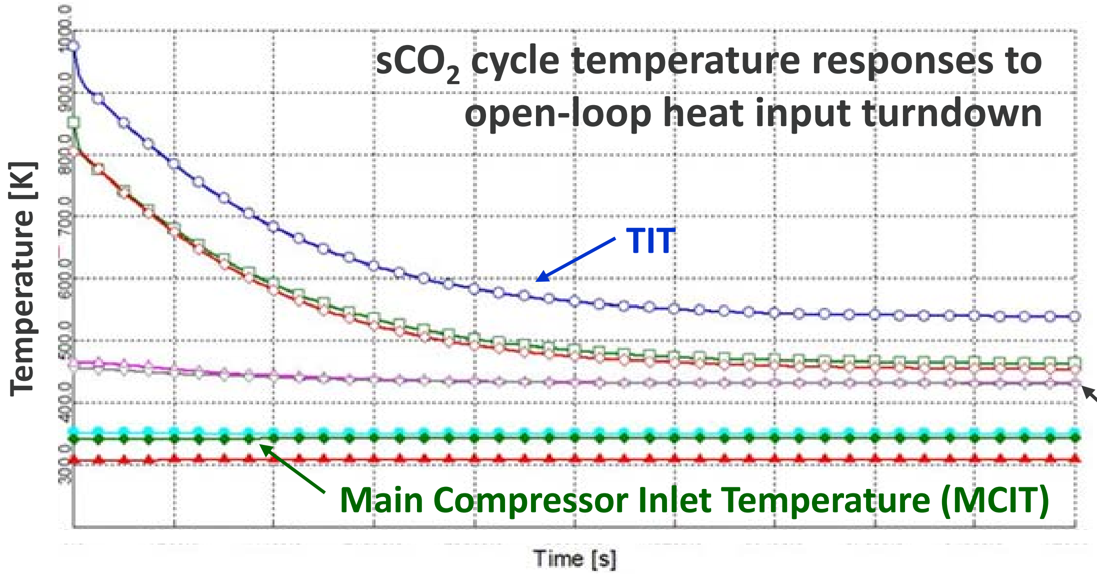
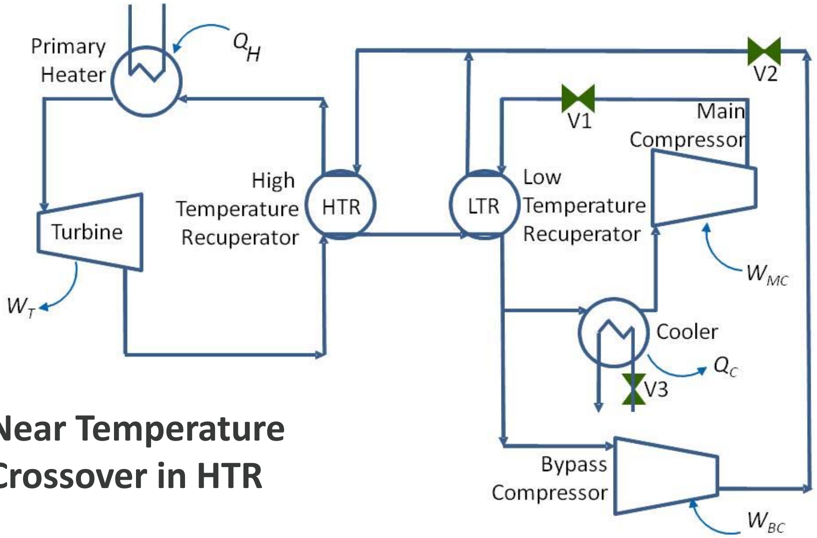
Transient Study: Part-Load Operation

“Open-Loop” Heat Input Turndown

- Over 40% maximum heat input turndown ($\dot{W}_{net}=0$)
- Near temperature crossover in high temperature recuperator (HTR)
- Large decrease in turbine inlet temperature (TIT)



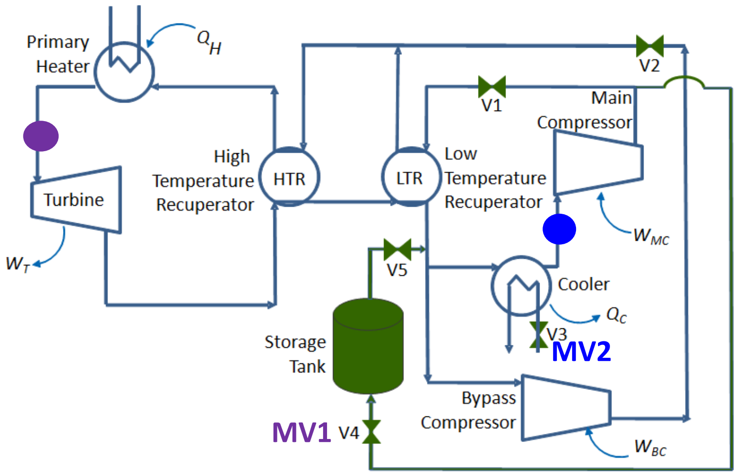
Near Temperature Crossover in HTR



Transient Study: Part-Load Operation

“Closed Loop” Heat Input Turndown

- **Goal: Maintain high cycle efficiency during turndown in heat input ($Q = MC_p \Delta T$)**
- **To transfer less heat (Q), the cycle ΔT or mass flow rate (M), must decrease**
- **When considering ΔT, recall that Carnot cycle efficiency ($\eta = 1 - T_{cold}/T_{hot}$)**
  - Carnot cycle efficiency is maximized by keeping the cycle T_{hot}/T_{cold} as high as possible
  - T_{hot} = TIT (Design point, 973.2 K, material constraint)
  - T_{cold} = MCIT (Design point, 306.6 K, 2.5 K above CO_2 critical T)
- **Thus to achieve high efficiency, reduce mass flow**
  - Inventory Control ($M_{inventory} = \Sigma \rho_i V_i$)
    - Remove mass from the cycle after main compressor
    - As mass is removed, cycle pressure decreases (sliding pressure)
    - Turbomachines respond based on performance curves
- **Other control measures are required to maintain high efficiency operation while satisfying process constraints**



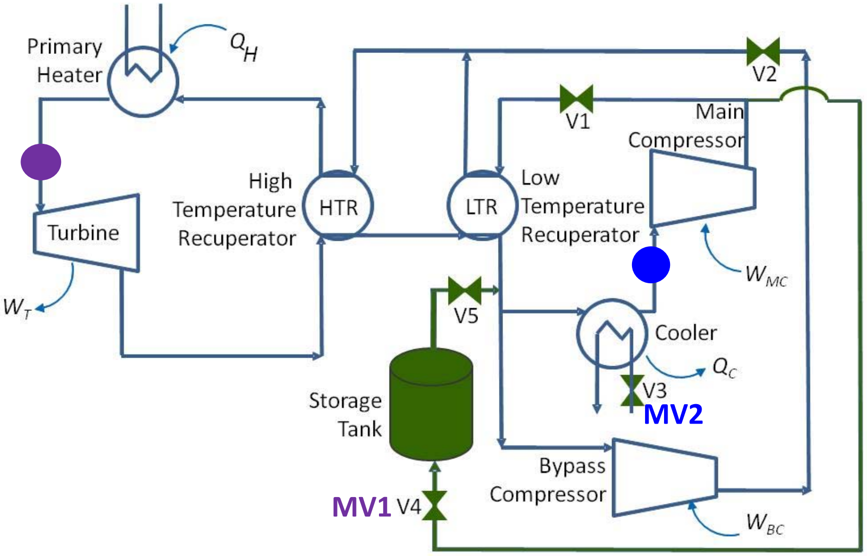
Heat Input Turndown

Inventory Control

- **Objective**
  - Maximize efficiency (net power/heat input)
- **Operating Constraints**
  - ● **TIT ≤ Upper bound** [MV1, MV2]
    - **Design point, 973.2 K** (material constraint)
  - ● MCIT ≥ Lower bound [MV2]
    - Design point, 306.6 K (2.5 K above CO_2 critical temperature)
- **Manipulated Variables (MV)**

  MV1: Storage valve (V4) | TIT

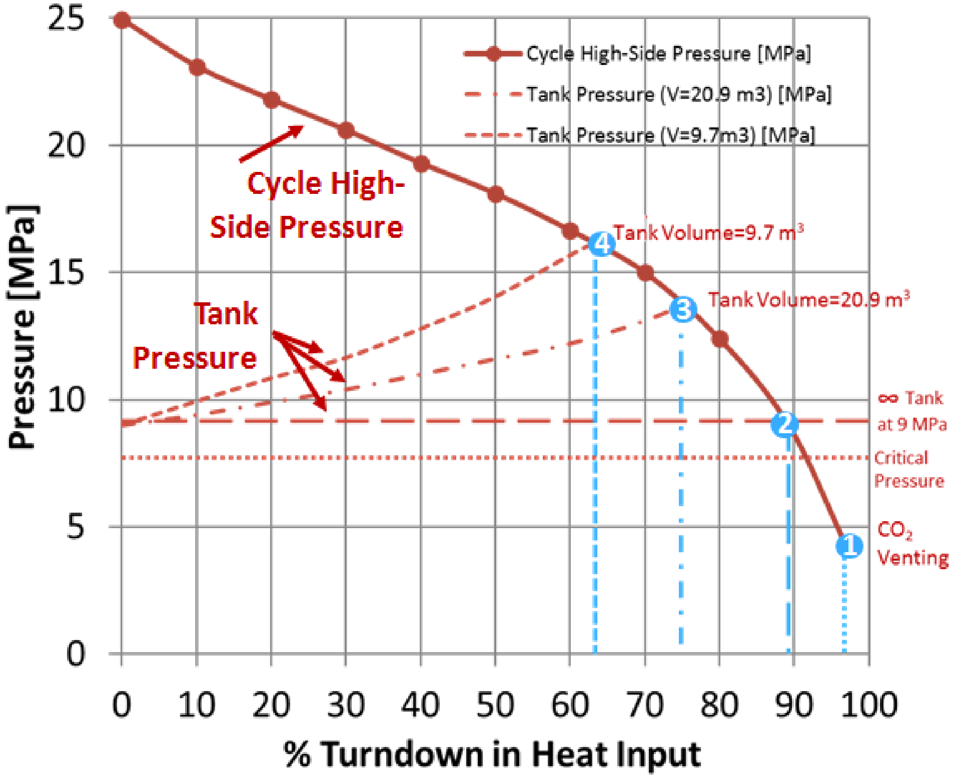
  MV2: Cooling water flow (V3) | MCIT
- **Operating Strategy**
  - Reduce inventory to maintain TIT until tank P equals cycle high P, then let TIT drop until W_{net}=0 MWe
- **Case Studies: Impact of CO_2 Storage Capacity and Pressure**
  - No storage tank (CO_2 venting to atmosphere)
  - Infinitely large storage tank with an initial pressure of 9 MPa, slightly above cycle low-side pressure
  - Two storage tanks with different volumes, both starting an initial pressure of 9 MPa



Heat Input Turndown – Inventory Control

Case Studies: Impact of CO_2 Storage Capacity and Pressure

Case Study	(1)	(2)	(3)	(4)
Storage Tank Volume [m^3]	Vent	∞	20.9	9.7
Initial Tank Pressure [MPa]	0.1	9.0	9.0	9.0
Pressure Pinch: Tank P = Cycle High P [MPa]	NA	9.0	13.7	16.3
Turndown [%] at Pressure Pinch Point	NA	89.4	75.0	62.0
Highest Turndown [%] with TIT at Design	97.0	89.4	75.0	62.0



Highest turndown keeping TIT at design

Heat Input Turndown – Inventory Control

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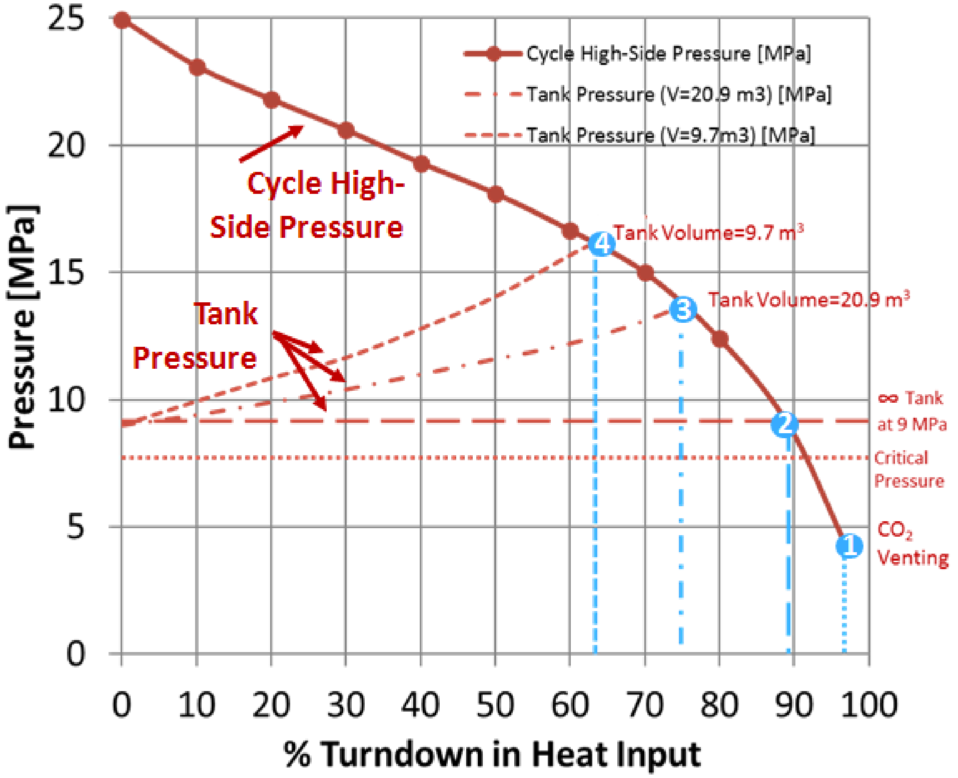
Highest Turndown [%] with TIT at Design	97.0	89.4	75.0	62.0
Maximum Turndown [%] at W_{net} = 0 MWe	97.0	92.3	86.6	83.0
TIT at Maximum Turndown [K]	973.2	803.0	687.3	638.2
% CO2 in Storage Tank	88.6	68.0	52.9	36.7

- **Remarks**
  - Larger storage tank capacity provides higher efficiency and greater maximum turndown, while maintaining higher TIT.
  - Cost and operational analyses are required to determine optimal tank size.

Highest turndown keeping TIT at design



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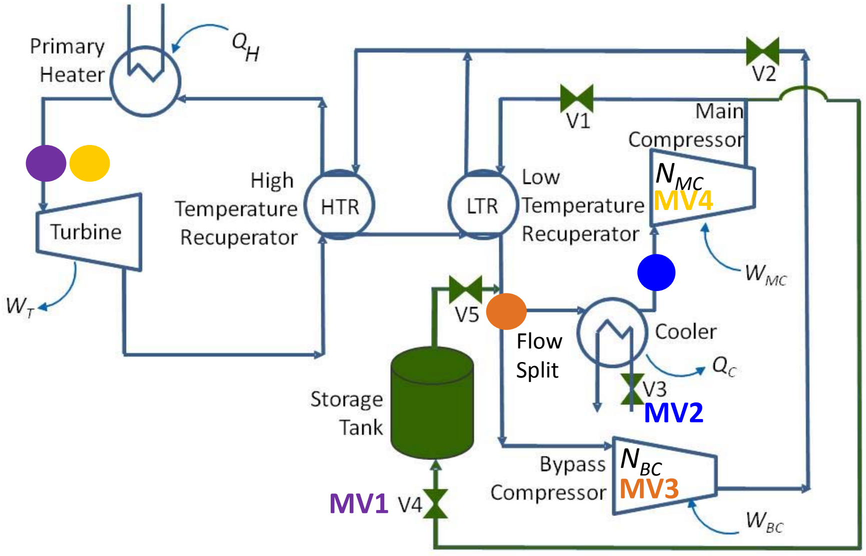
Heat Input Turndown

Inventory, Flow Split, and Flow Rate Control

- **Objective**
  - Maximize cycle efficiency using inventory, flow split, and flow rate control
- **Operating Constraints**
  - ● **TIT ≤ Upper bound** [MV1, MV2]
    - **Design point, 973.2 K** (material constraint)
  - ● MCIT ≥ Lower bound [MV2]
    - Design point, 306.6 K (2.5 K above critical temperature)
  - ● Bypass compressor surge point [MV3]
  - ● Main compressor surge point [MV4]
- **Manipulated Variables (MV)**

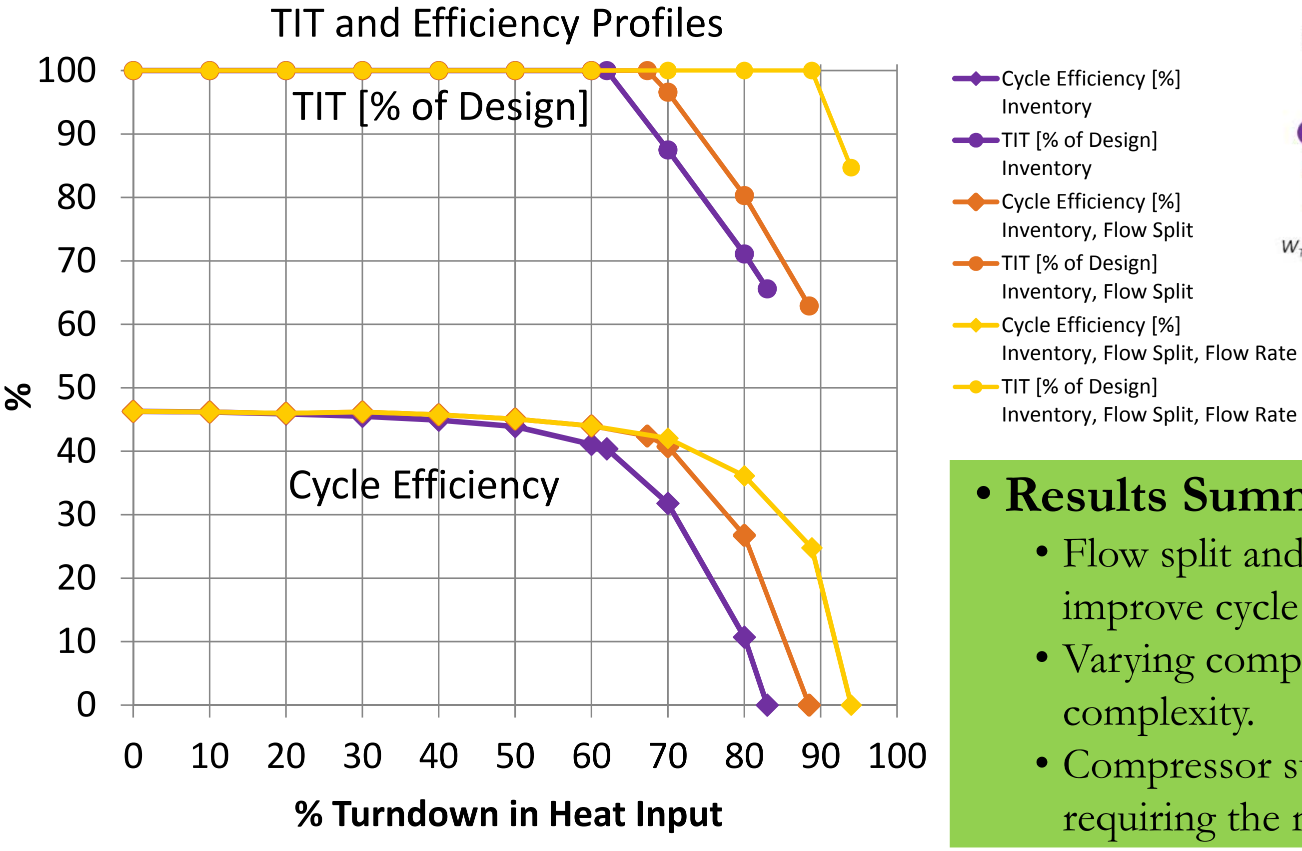
MV1: Storage valve (V4) | TIT
MV2: Cooling water flow (V3) | MCIT
MV3: Bypass compressor speed (N_{BC}) | Flow Split
MV4: Main compressor speed (N_{MC}) | Flow Rate

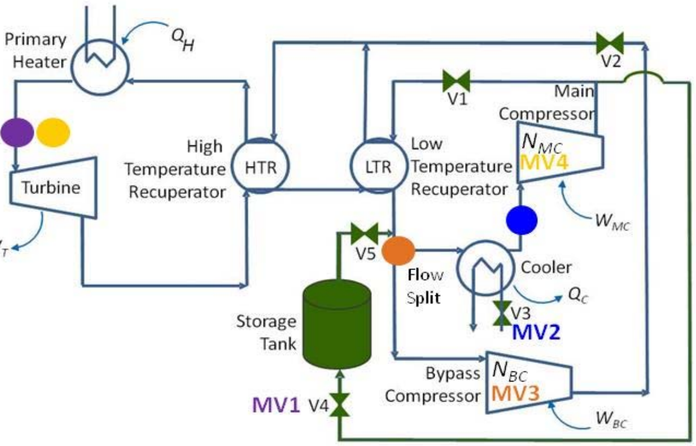


Operating strategy: Adjust flow split during turndown to increase efficiency. Once storage tank is full, reduce overall cycle flow rate to keep TIT at design by reducing main compressor speed until reaching surge.

Heat Input Turndown – Impact of Flow Split and Flow Rate Control

Storage Tank with Volume = 9.7 m^3 and Initial Pressure = 9 MPa





- **Results Summary**
  - Flow split and flow rate control increase TIT and improve cycle efficiency.
  - Varying compressor speed adds operational complexity.
  - Compressor surge limits become a factor at low load, requiring the need for surge control.

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Conclusions

- **Developed steady-state design and pressure-driven dynamic model of 10MWe sCO_2 recompression Brayton pilot plant**
- **Analyzed operating strategies for maximizing cycle efficiency during heat input turndown, while satisfying process constraints**
  - For inventory control, storage capacity and initial tank pressure impact cycle efficiency and maximum turndown. Larger capacity enables greater turndown.
  - Inventory control using storage tank with volume of 9.7 m^3 and initial pressure of 9 MPa provides over 80% turndown.
  - Flow split and flow rate control improve on cycle performance.
  - Maximum turndown over 90% is achievable using a combination of inventory, flow split, and flow rate control.
  - Efficiencies over 40% are maintained through 70% turndown.

Future Work

10 MWe sCO_2 Recompression Brayton Cycle

- **Dynamic Modeling**
  - Enhance turbine design and performance maps
  - Compact heat exchangers (Jiang, **Liese**, Zitney, Bhattacharyya, Modeling & Control 3, Paper #12,)
- **Transient Operations and Control**
  - Load-following operation and control (Mahapatra, Albright, **Liese**, and Zitney, Modeling & Control 1, Paper #25)
  - Startup and shutdown
  - Turbine controls and compressor surge control
  - Advanced process control, including model predictive control
- **Sensors**
  - Optimal sensor network design
  - Disturbance rejection, state estimation, condition monitoring, fault diagnosis, …
- **Validation**
  - Exploit data from STEP pilot plant test facility
  - Validate dynamic models, controls, and sensor network

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

STEP

sCO_2 Technology

Turbomachinery

Advanced Concepts for Direct-Fired Cycles

Systems Integration and Optimization

Recuperators

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