sCO_2 Cycle Modeling at ANL: Performance, Optimization, Control, and Dynamics

Anton Moisseytsev
Argonne National Laboratory, USA

The 5th International Symposium - Supercritical CO_2 Power Cycles
National Laboratories R&D Panel
San Antonio, TX
March 29-31, 2016

Motivation and Approach

- sCO_2 Cycle modeling at Argonne started in 2001
  - NERI + Ph.D. Dissertation -> Gen IV -> AFCI -> ARC -> SMR -> ART
- Needed answers to fundamental questions
  - What is the cycle efficiency?
  - Is cycle better than steam?
  - What it takes to achieve the performance?
  - Can you control the cycle close to critical point?
  - What is transient response of the cycle? For nuclear power plants, need to calculate operational transients and postulated accidents for safety evaluation
- Solution: create a first-principal but realistic code
  - Ability to modify, improve, and extend the code as knowledge on the cycle grew
  - Be able to couple to Argonne reactor analysis codes
  - Sufficient detail to serve as “simulation experiments”

ANL Plant Dynamics Code (PDC)

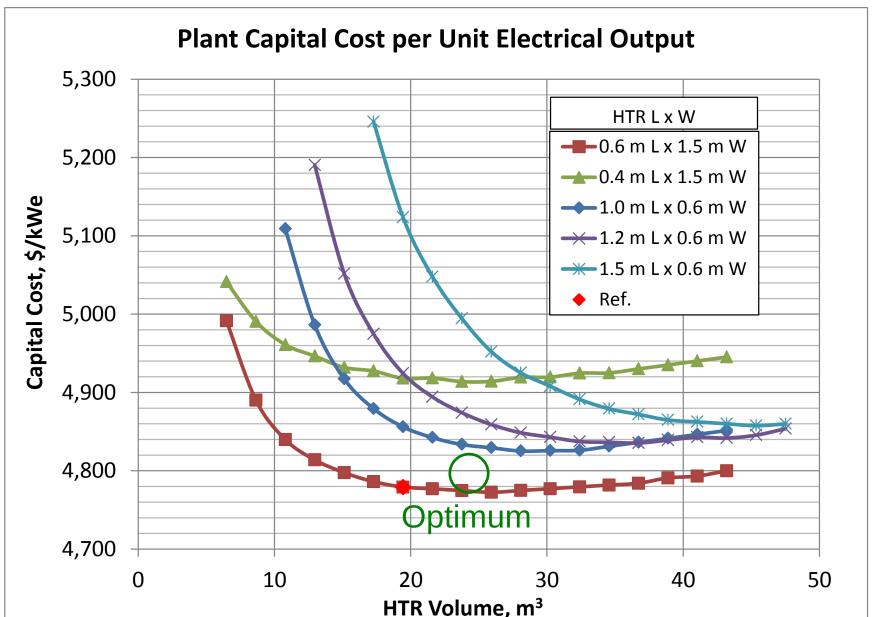
- Specifically developed for analysis of S-CO_2 cycle
  - One-dimensional system level transient analysis code
  - Targets the specific features of the cycle
    - Operation close to the critical point
    - Recompression cycle (if needed)
  - Real CO_2 properties
    - Property variations in HX's and turbomachinery
    - No simplifying ideal gas assumptions
    - Compressibility effects
- Incorporates S-CO_2 cycle control mechanisms and logic
- Incorporates steady-state design code to determine cycle initial conditions
- Design and performance subroutines for both turbine and compressor
- Coupled to SAS4A/SASSYS-1 that performs reactor dynamic analysis

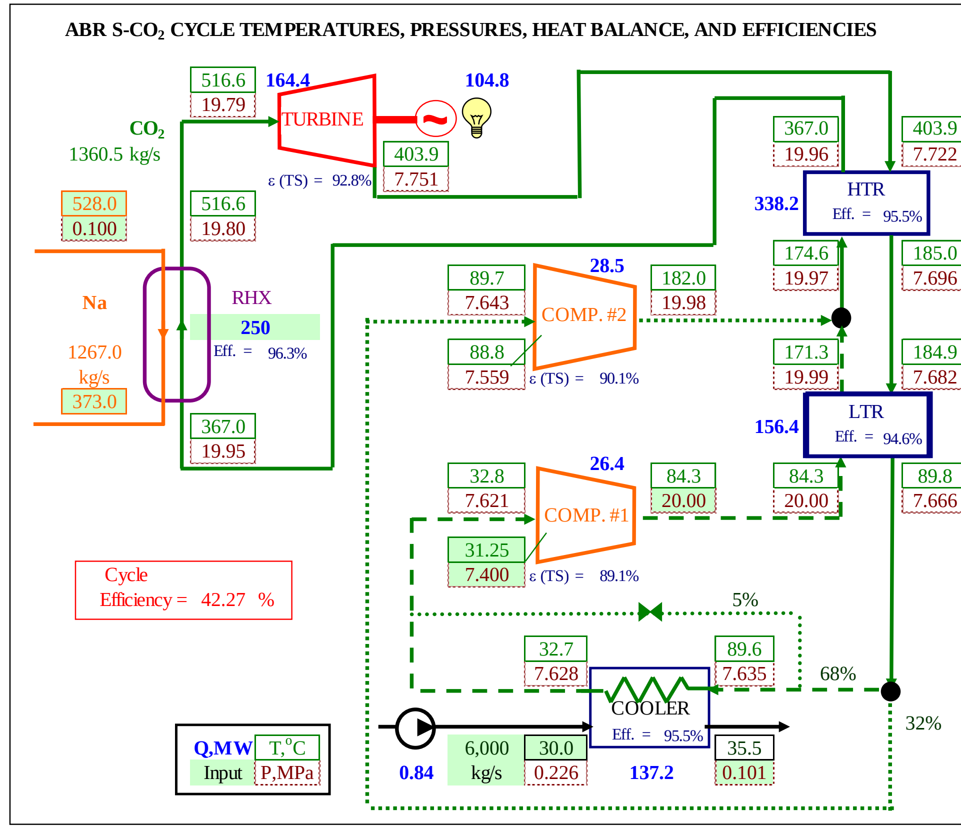
- Validation of the PDC against the SNL RCBC and BMPC IST data is ongoing

Steady-State Performance & Optimization

- Calculate design performance for the cycle (efficiency) and each component (effectiveness, pressure drop)

- Trade-off and optimization
  - Operating conditions (e.g., pressures)
  - HX size and performance *vs* cost





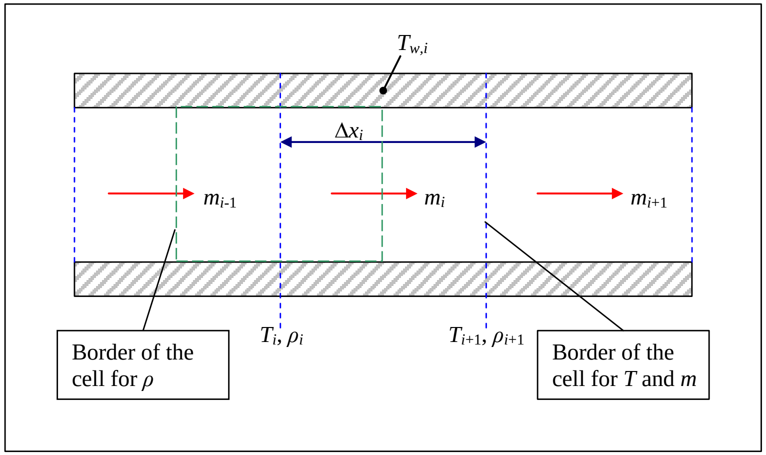
"sCO2 Cycle Modeling at ANL" by A. Moisseytsev, 5th S-CO2 Symposium, San Antonio, TX, March 29-31, 2016

Transient Analysis

- For nuclear applications, transient performance of the cycle is also important
  - Cycle control and load following
    - E.g., integration with autonomous reactor control
  - Accident conditions – how they affect **reactor safety**
    - E.g., Postulated CO_2 pipe break = A nuclear power plant design basis accident
- Transient part of the PDC also developed to account for specifics of operating near the critical point
  - Properties variation in HXs and turbomachinery
  - No ideal gas assumptions
  - Compressibility effects
  - Equations are written to account for properties

$$\begin{cases} \dfrac{\partial h_{i+1}}{\partial t} = \dfrac{1}{M_i}\dfrac{\dot m_i + \dot m_{i-1}}{2}\left(h_i - h_{i+1}\right) + \dfrac{\Delta x_i N_t}{M_i res_{w,CO_{2i}}}\left(T_{w,i} - \dfrac{T_i + T_{i+1}}{2}\right) \\ \dfrac{\partial \rho_i}{\partial t} = \dfrac{1}{A\left(\dfrac{\Delta x_i}{2} + \dfrac{\Delta x_{i-1}}{2}\right)}\left(\dot m_i - \dot m_{i-1}\right) \\ \dfrac{\partial \dot m_i}{\partial t} = \dfrac{A}{\Delta x_i}\left(p_i - p_{i+1}\right) - \dfrac{2 f_i \Delta x_i}{M_i D_h}\dot m_i^2 \end{cases}$$

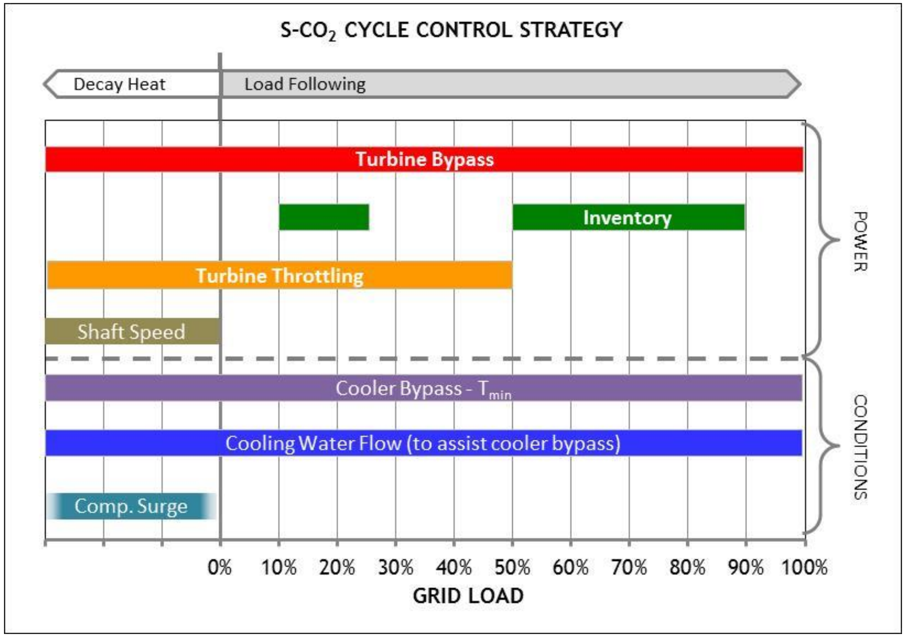
$$\begin{cases} \dfrac{\partial h}{\partial t} = \left(\dfrac{\partial h}{\partial T}\right)_\rho \dfrac{\partial T}{\partial t} + \left(\dfrac{\partial h}{\partial \rho}\right)_T \dfrac{\partial \rho}{\partial t} \\ \dfrac{\partial p}{\partial t} = \left(\dfrac{\partial p}{\partial T}\right)_\rho \dfrac{\partial T}{\partial t} + \left(\dfrac{\partial p}{\partial \rho}\right)_T \dfrac{\partial \rho}{\partial t} \end{cases}$$

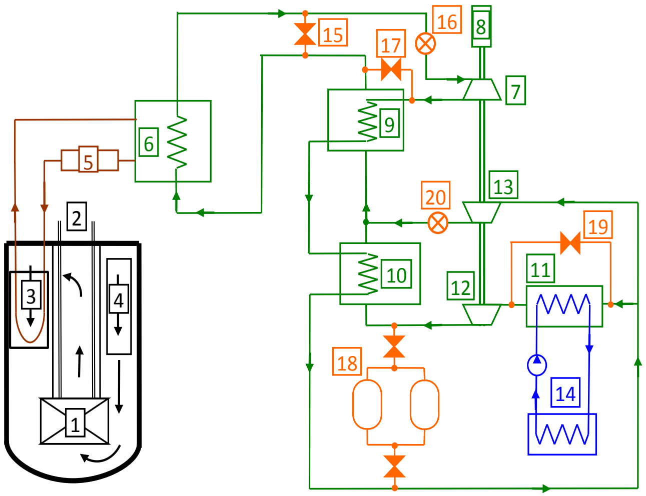


Control System Development

- Significant effort was devoted to developing cycle control approach
  - Grid load following
  - Decay heat removal mode
  - Controllability near the critical point
  - Interaction with reactor control

- Combination of various control mechanisms is **required**



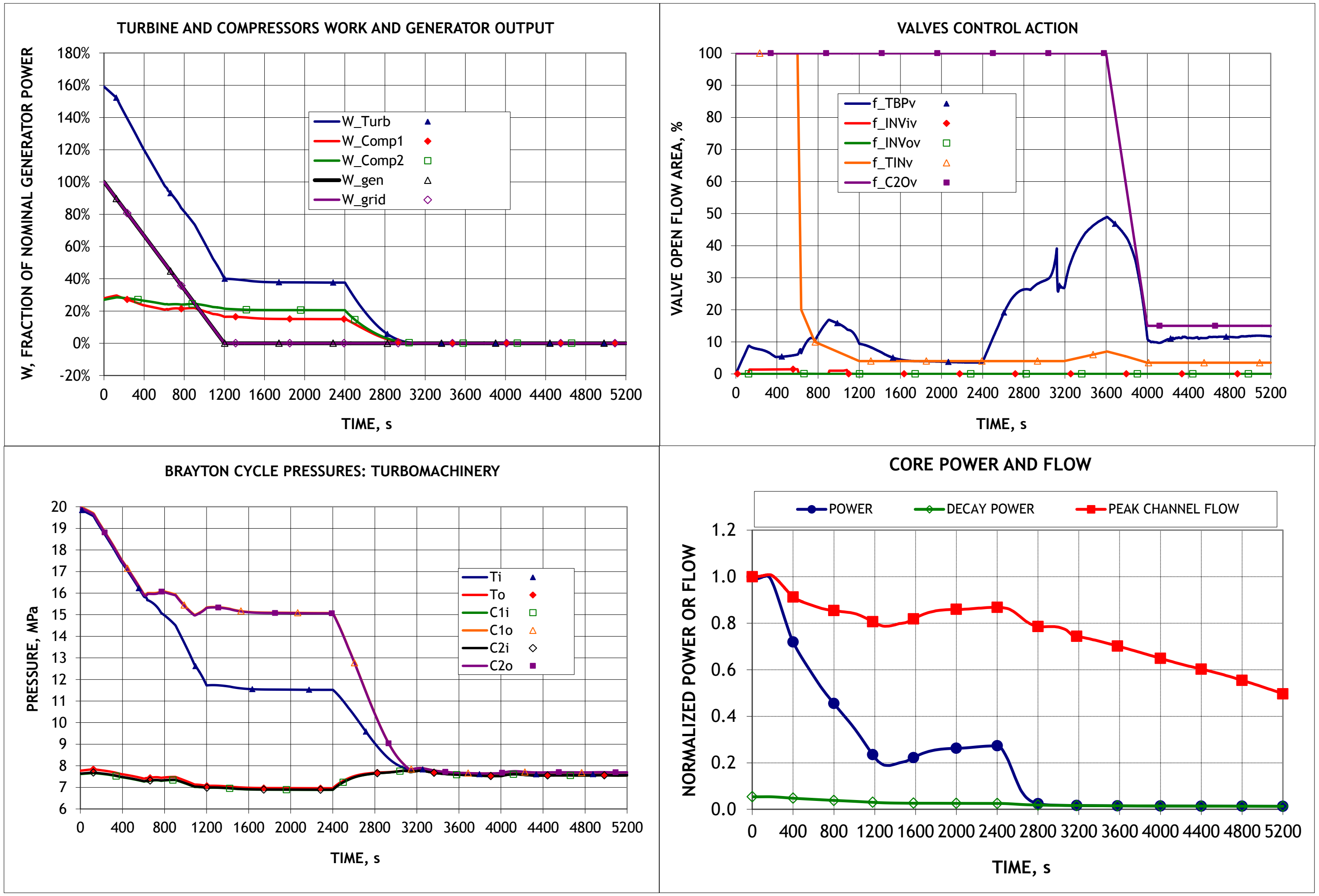


1 – Reactor core
2 – Control rods
3 – Intermediate Heat Exchanger
4 – Primary Na Pump
5 – Intermediate Na Pump
6 – Na-to-CO_2 heat exchanger
7 – CO_2 turbine
8 – Generator
9,10 – High and low temperature recuperators
11 – Cooler
12,13 – Compressors
14 – Cooling circuit and control
15 – Na-to-CO_2 heat exchanger bypass valve
16 – Turbine throttling valve
17 – Turbine bypass valve
18– Inventory control
19 – Cooler bypass valve
20 – Compressor throttling valve

"sCO2 Cycle Modeling at ANL" by A. Moisseytsev, 5th S-CO2 Symposium, San Antonio, TX, March 29-31, 2016

Example of Transient Calculations

- Load following from 100% to 0% followed by disconnection from the grid and transition to decay heat removal mode

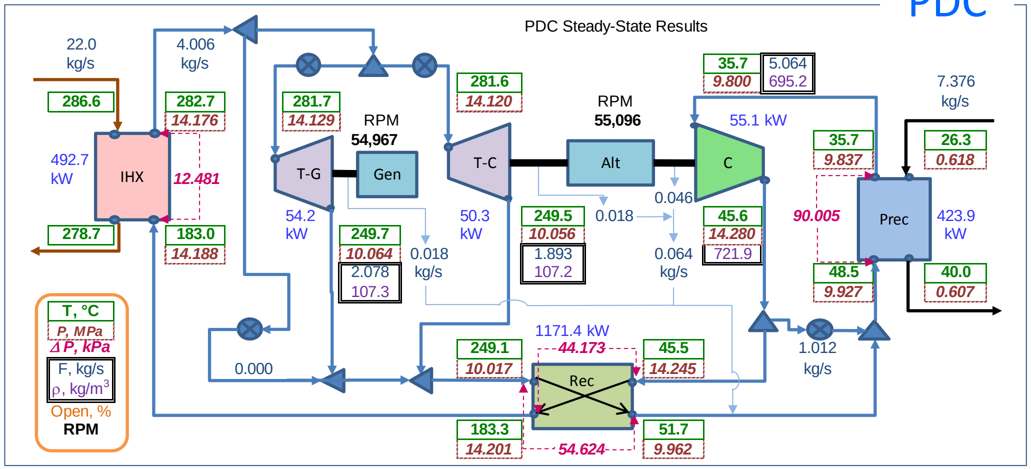


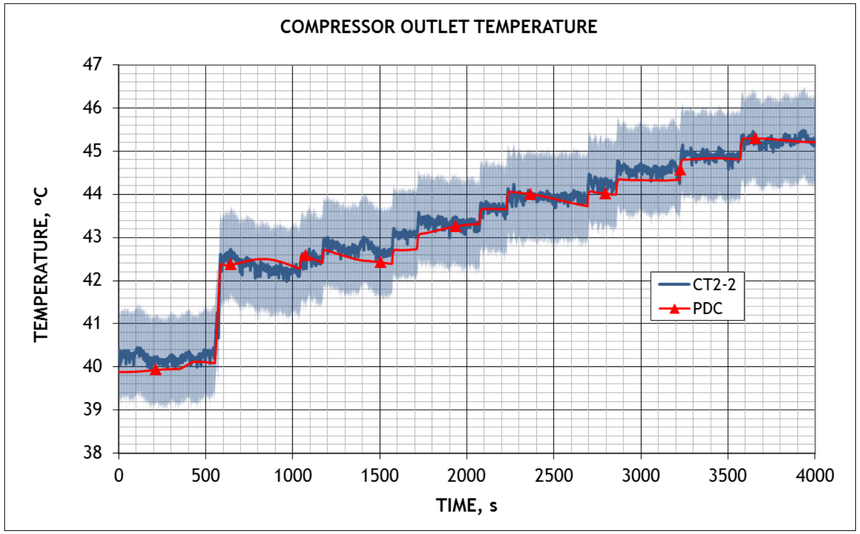
"sCO2 Cycle Modeling at ANL" by A. Moisseytsev, 5th S-CO2 Symposium, San Antonio, TX, March 29-31, 2016

PDC Validation

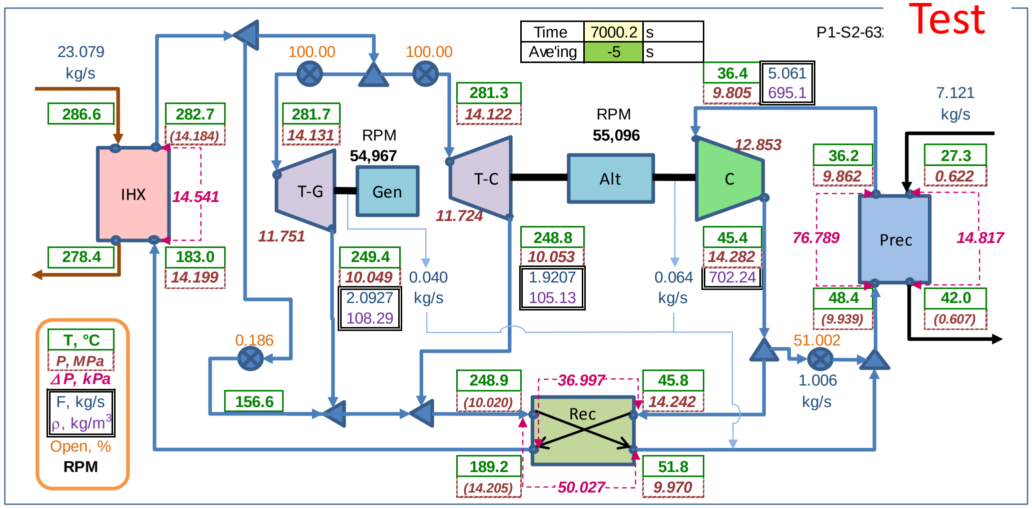
- Validation is an essential part of code development
  - PCHE tests at Argonne
  - SNL Recompression Closed Brayton Cycle facility
  - BPMC Integrated System Test
- Both steady-state and transient data

PDC





Test



"sCO2 Cycle Modeling at ANL" by A. Moisseytsev, 5th S-CO2 Symposium, San Antonio, TX, March 29-31, 2016

Future Plans

- Continue PDC validation moving on to data from larger-scale facilities (STEP, etc.)
- Application of the PDC to dry air-cooled sCO_2 cycles
- Investigation of potential benefits of Model-Based Predictive Control and other advanced control methodologies
- Applications to other heat sources than nuclear (fossil, solar)