Evaluation on the rapidity of sCO2 cycle power up and down events using the STEP dynamic simulation model

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- Fusion – Need for rapid shutdowns and startups (Jack)

- Study – Can an sCO2 cycle meet the rapid startup and shutdown profile of the fusion plant (Michael)
  - Methodology and results
  - Importance of study

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What is fusion?

- Fusion is the process that powers the sun and stars by fusing hydrogen at the core
- Unlike its fission counterpart, fusion relies on fusing two lighter atomic particles. The mass deficit of the subatomic particles releases energy ($e=mc^2$)

Why fusion?

- Fusion energy is low carbon, abundant, and secure

STEP*uk: The fusion prototype powerplant

*STEPuk =Spherical Tokamak for Energy Production

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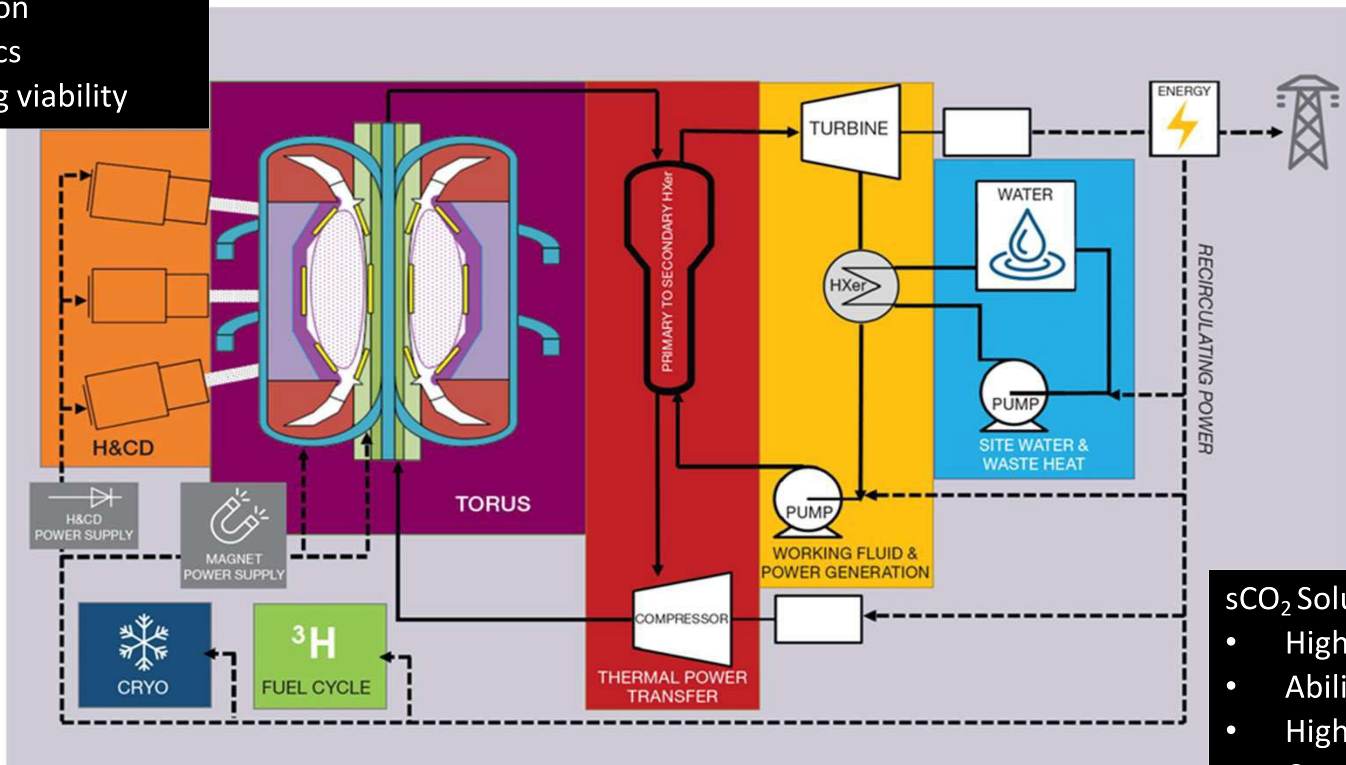
Fusion powerplant challenges
- Parasitic loads
- Heat integration
- Rapid dynamics
- Demonstrating viability



sCO_2 Solution space
- High efficiency
- Ability to integrate heat
- Highly responsive
- Compact and competitive

Flexibility drivers of STEP$_{UK}$

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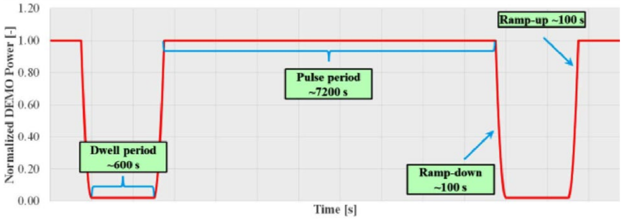
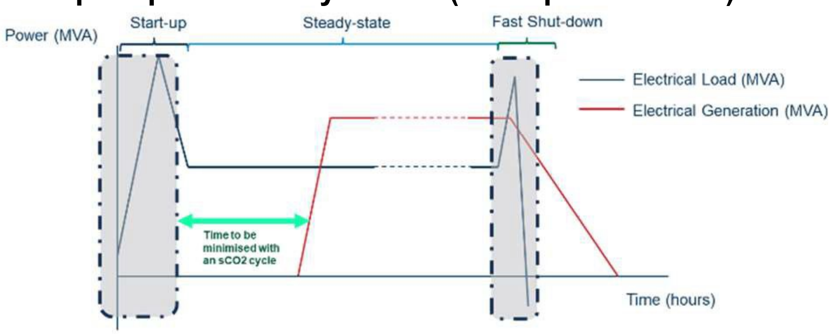
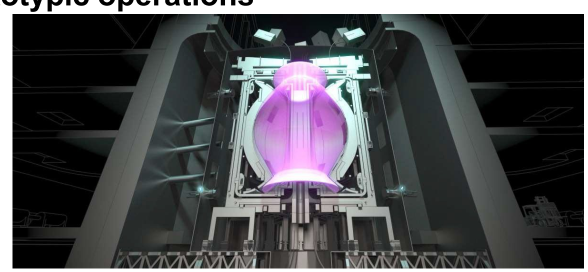
1. Inherently pulsed



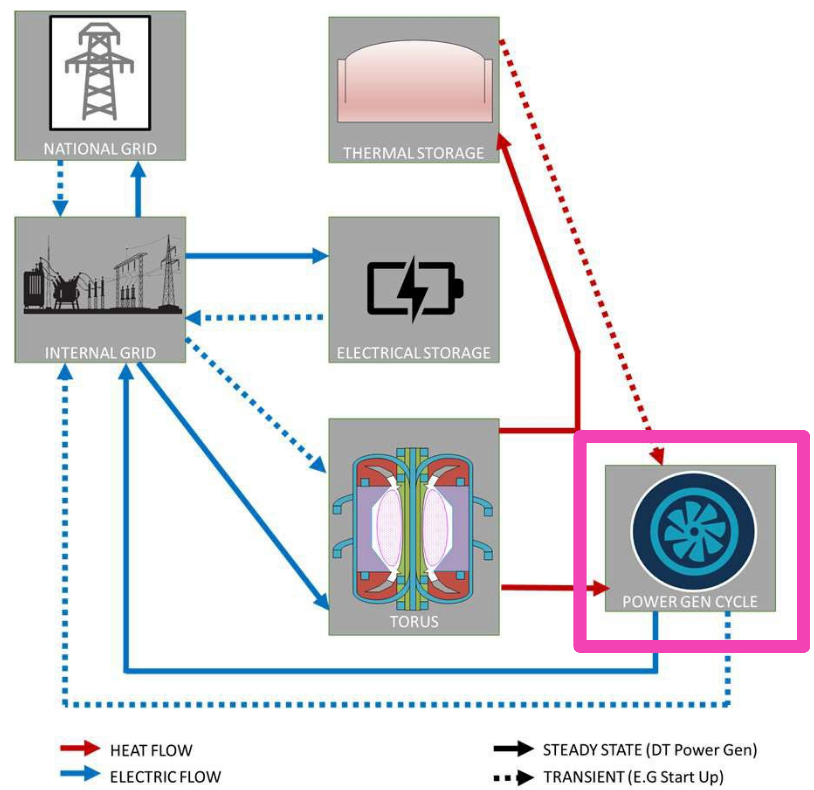
2. Rapid operational dynamics (startup/shut down)



3. Prototypic operations



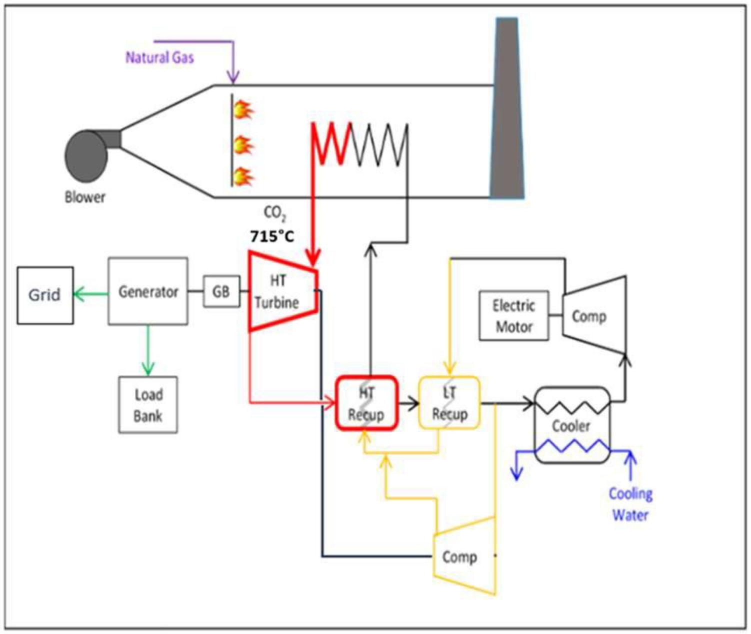
Solution Space & Actuators



L. Barucca et al.; Maturation of critical technologies for the DEMO balance of plant systems, Fusion Engineering and Design, Volume 179, 2022

Can an sCO2 cycle meet the rapid startup and shutdown profile of the fusion plant? Study methodology and results

- Methodology
  - Used the STEPUS dynamic simulation model
    - Recompression Brayton Cycle (RCBC) configuration
    - Model provides a representation of a commercial powerplant
    - Improved thermal modelling of some components
  - Define component thermomechanical ramp rate maximums
  - Evaluate limits on the rapidity of power up and down events



Simplified Diagram of RCBC Configuration

Study methodology and results

Representative equipment mechanical limits related to start-up and shutdown results

- Used STEP component thermomechanical limitations as indicators of large powerplant transient limits
- HTR, turbine stop valve and turbine see the highest transients

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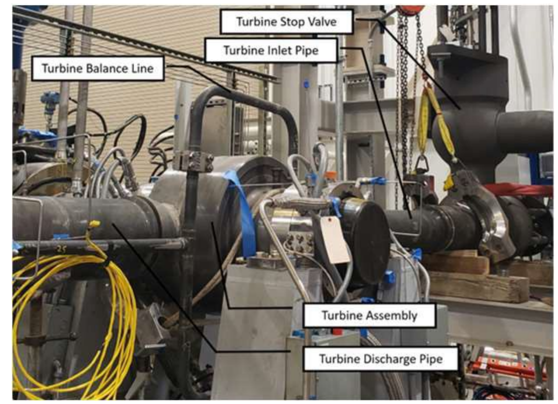
- Turbine stop valve not specified & evaluated for significant transients, not used as a limiting component
- Turbine designed to ramp from ambient to 715°C in 30 minutes
- HTR design did not define a maximum allowable ramp rate
  - Other analysis estimated a maximum ramp rate of 4°C to 7°C /min
  - Sandia National Laboratory sCO2 loop ramped at 20°C/min, limited by HTR
  - Used 7°C /min, accepted 8°C /min over 16°



Study methodology and results

RCBC Modelling Results – Start-up & Shutdown

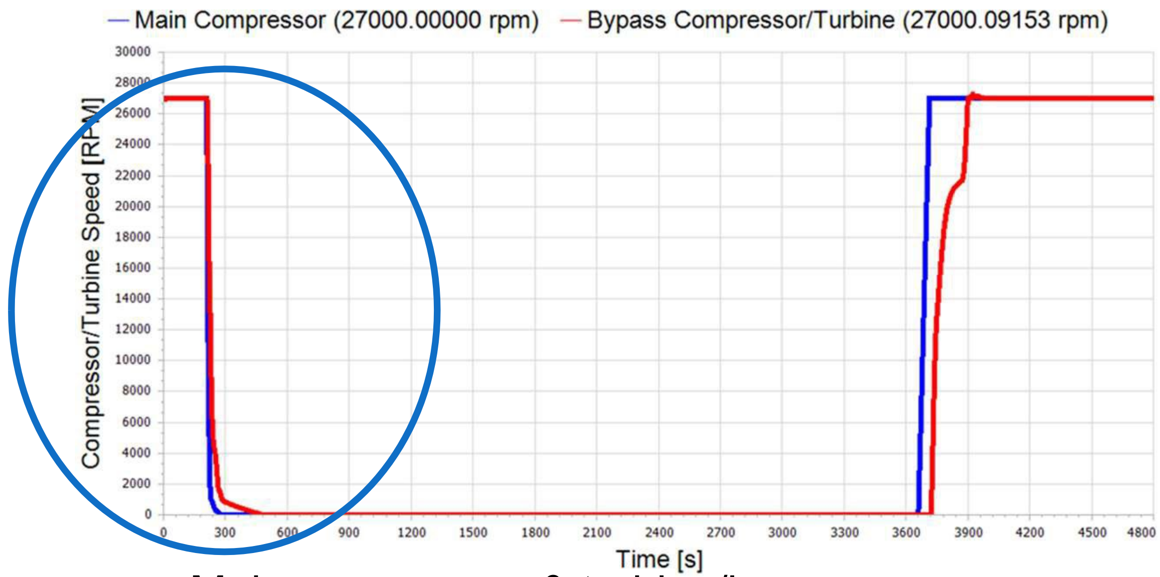
- The simulation starts at the normal operating condition, followed by a shutdown of the heat source for shutdown of the system

- The shutdown is like a system trip where the heater shuts off and the TSV closes quickly causing hot, high-pressure CO2 in the region of the heater to be bottled up.

- After system shutdown, it is in a standby hold condition for one hour, after which the system is re-started to full power operating condition while keeping plant equipment within operating limits.

Study methodology and results - shutdown

- Steady state speed of both shafts is 27,000 RPM
- Roughly one minute for the main compressor to spin down to zero speed
- Four minutes for the turbine/bypass compressor to spin down due to higher inertia

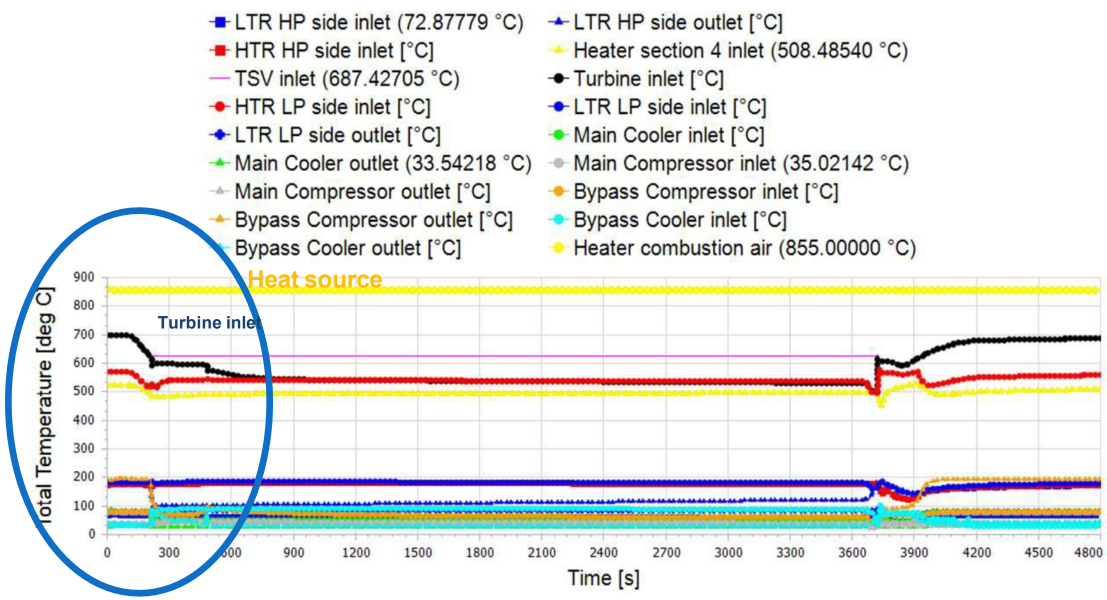


Main compressor & turbine/bypass compressor shaft speeds

Study methodology and results – shutdown

- Heat input kept at 855C boundary condition
- Turbine inlet temperature is initially 700C. The heater starts to shut down and flow decreases starting at 60 seconds and ending at 120 seconds
- The system continues to run, and turbine inlet CO2 decreases to 625C (turbine power decreases to 10.7 MWe) before shutdown of the remainder of the system begins.

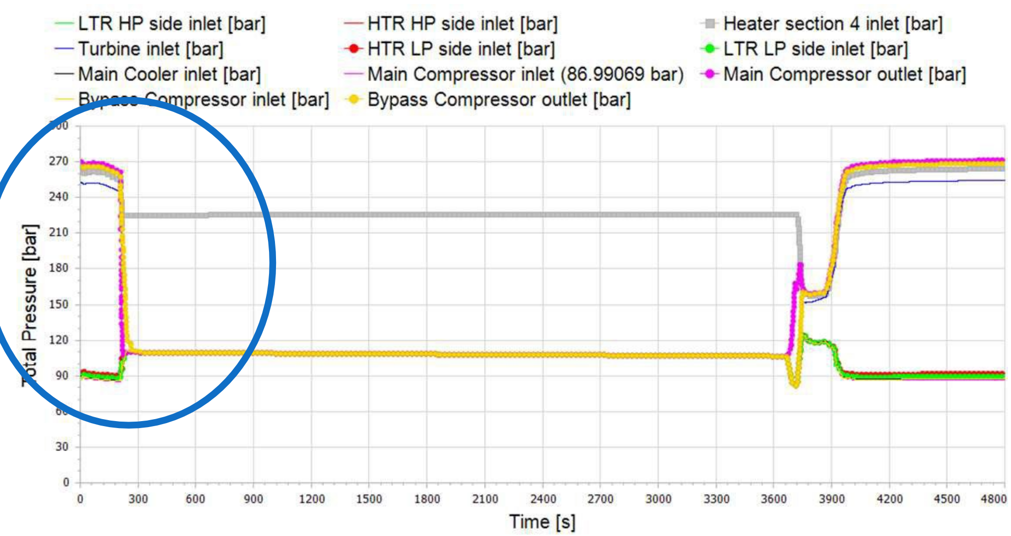
CO2 temperatures throughout the system



Study methodology and results – shutdown

- After heater shutdown, pressures start a decrease until the remainder of the system shuts down
- Once the compressor recycle valves open and compressors spin down, system reaches settle out pressures
- Higher pressure holds between the turbine stop valve and check valves (grey data line)

CO2 pressures throughout the system

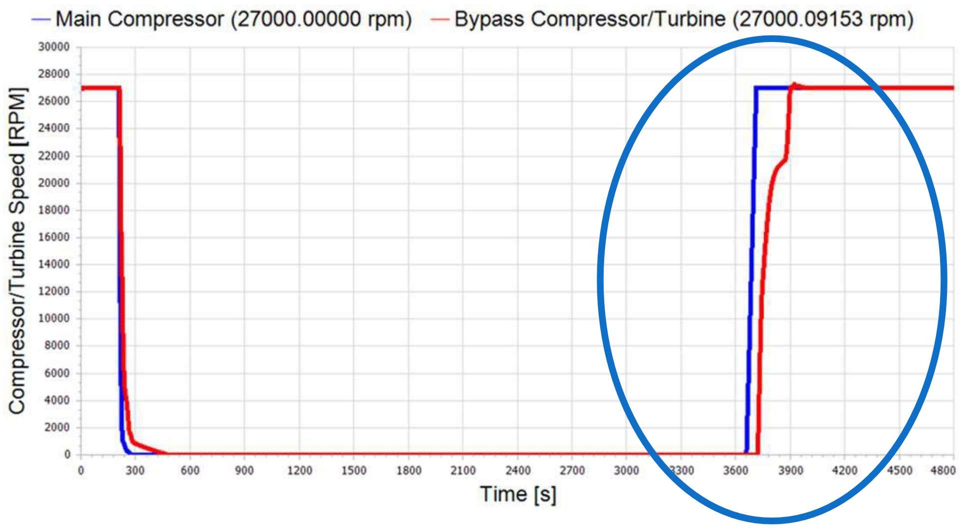


Study methodology and results

Start-ups to steady state from shutdown conditions

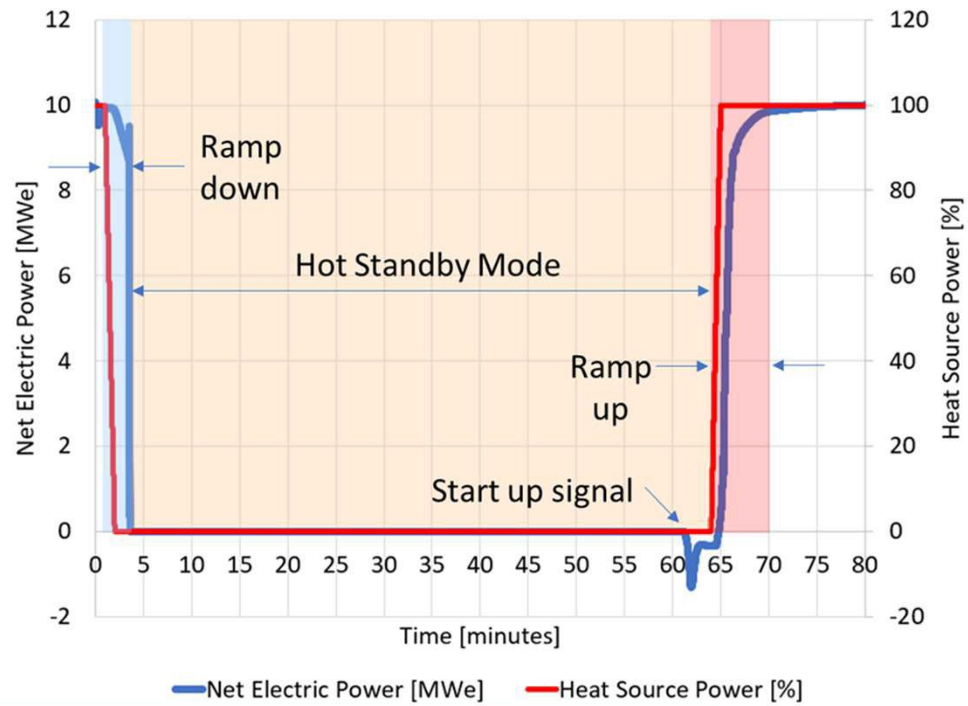
- Main compressor comes up first to 27,000
- Turbine (with bypass compressor on shaft) comes up as stop valve is opened, and main compressor recycle valve is closed, <5 minutes
- Real STEP gearbox temperatures limits speed increase - time to full speed would be ~12 minutes.
    - Specify startup performance when procuring the compressor

Main compressor and turbine/bypass compressor shaft speeds



Study methodology and results
Net electric power output

- Shutdown & startups take less than 5 minutes paced by rotating inertia
- The shutdown puts the system into a hot standby condition
- Hot standby temperatures fall slowly
- The startup command leads the net power up ramp
- A short period of negative power leads startup due to the motor driven compressor



Rapid ramp rates of the sCO2 power cycle could effectively support challenging operating scenarios

Importance of study

- Lessons learned
  - Thermal transients at components found to be acceptable
  - Turbomachinery rotating inertia can control startup & shutdown rates
  - System shuts down to hot standby condition, supports rapid ramp to power
  - Component specification should include the transient environment
    - Dynamic modeling must be done early in the design process
- The STEP dynamic simulation model is a valuable tool for powerplant design & evaluations
  - The model can be the starting point for a large powerplant sCO2 system model
  - Pursue continuous model improvement, validate with data from STEP operation
- Provides a key assessment of how the sCO2 cycle can be adapted to meet critical dynamic requirements of a fusion power plant.