sCO2 POWER CYCLE DEVELOPMENT, MODELING AND DEMONSTRATION AT STEP

Gas turbines in a carbon-neutral society

10th International Gas Turbine Conference

11-15 October 2021

Paper ID Number 35-IGTC21

Promise of sCO_2 Power Cycles

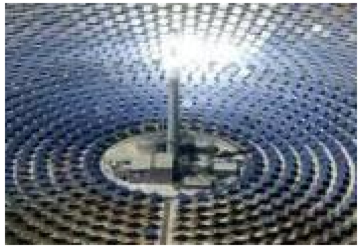
Promise:

> Efficient, Compact, Scalable, low water, low-carbon power generation

Plans to Demonstrate:

> Operability, Turbomachinery, Seals, Heat Exchangers, Durability, Materials, Corrosion, Cost

Versatile Technology – Broad Applicability:


Concentrated Solar


Fossil Fuel


Geothermal


Nuclear


Energy Storage

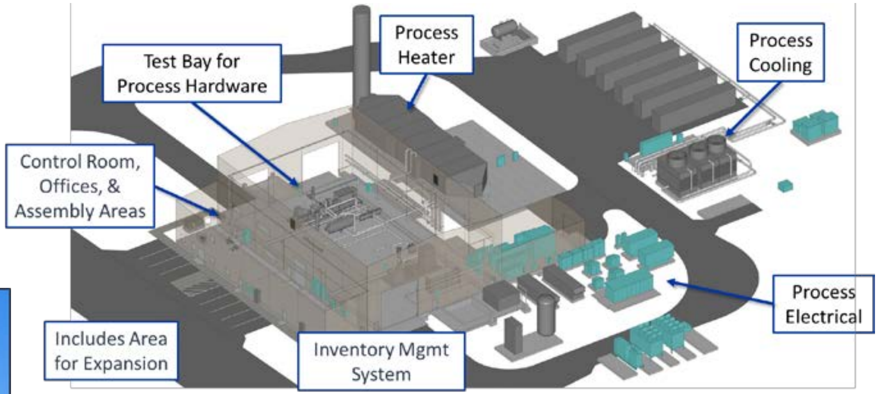

Waste Heat Recovery

Supercritical Transformational Electric Power (STEP) Project DE-FE0028979

Scope: Design, construct, commission, and operate **10 MWe sCO_2 Pilot Test Facility**
Reconfigurable to test new technologies in the future

Goal: Advance state of the art for high temperature sCO_2 power cycle performance
Evolve Proof of Concept (TRL3) to operational System Prototype (TRL7)

Schedule: Three budget phases over six years (2016-2023)
Currently in Budget Phase 2 – Fabrication & Construction



Team: U.S. Department of Energy (**DOE NETL**)
Gas Technology Institute (**GTI®**)
Southwest Research Institute (**SwRI®**)
General Electric Global Research (**GE-GR**)

Industry Partners:

STEP Program Objectives

STEP Demo will demonstrate a fully integrated functional electricity generating power plant using transformational sCO2-based power cycle technology

Demonstrate pathway to efficiency **> 50%**

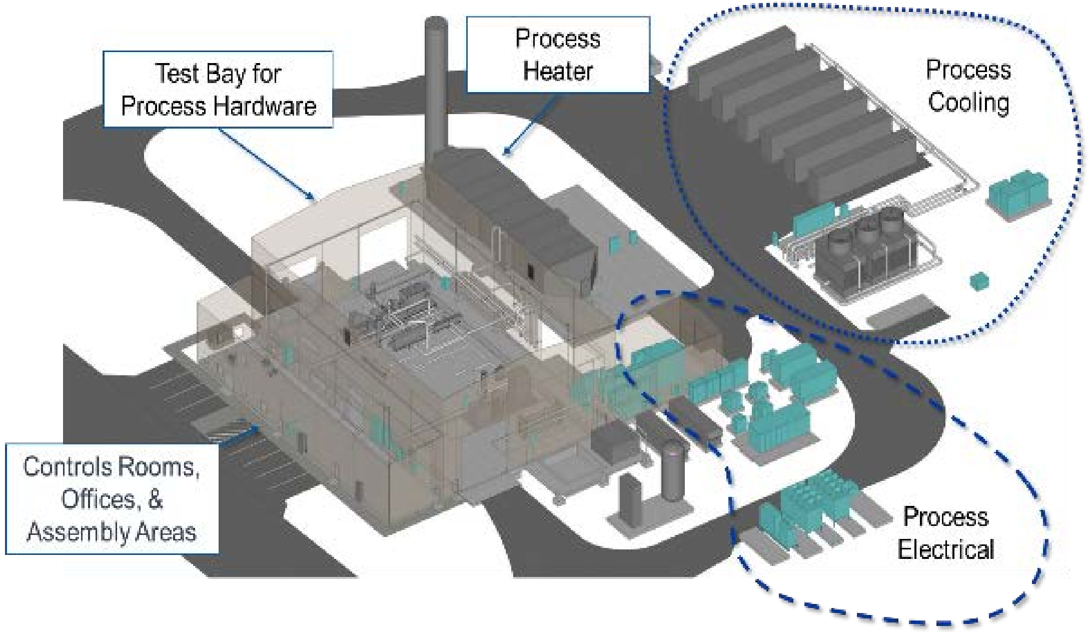
Demonstrate cycle operability **>700°C** turbine inlet temperature and 10 MWe net power generation

Quantify performance benefits:

- 2-5% point net plant efficiency improvement
- 3-4% reduction in LCOE
- Reduced emissions, fuel, and water usage

Demonstrate Reconfigurable flexible test facility

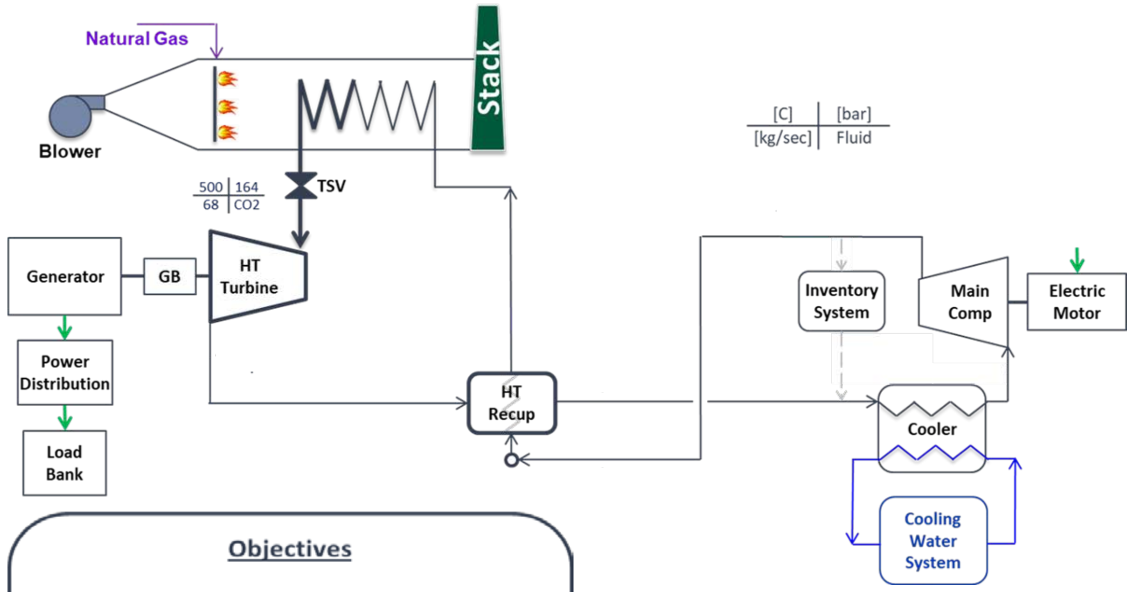
- Available for Testing future sCO2 equipment & systems



STEP will be among the largest demonstration facilities for sCO2 technology in the world

Simple and Recompression Brayton Cycle test configurations planned to achieve project objectives

Simple Recuperated Brayton Cycle

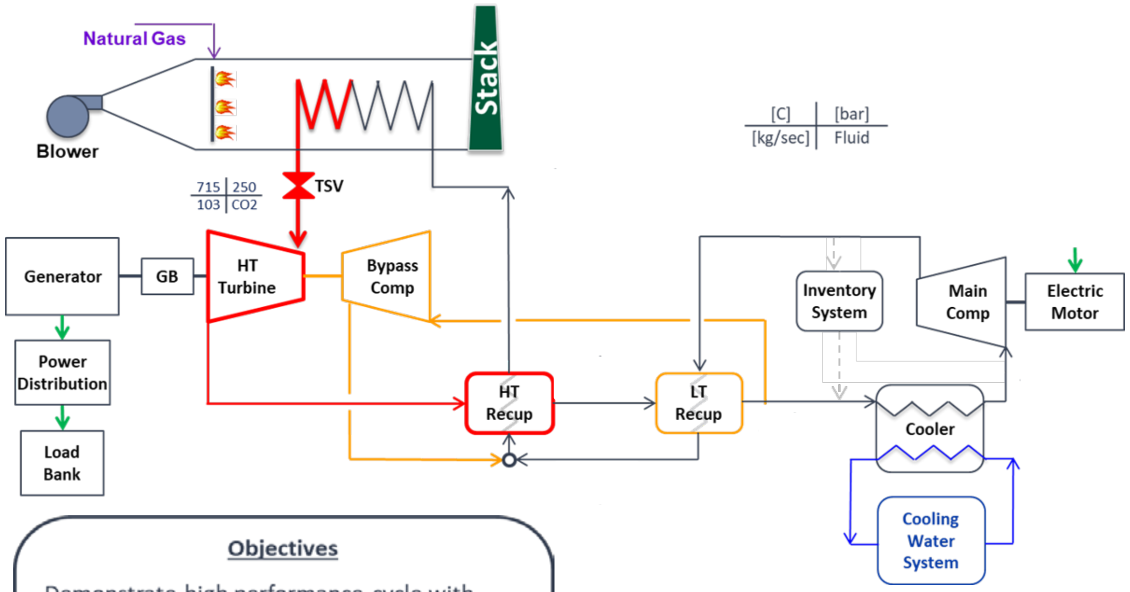


Objectives

Demonstrate initial cycle performance with reduced risk configuration

- Reduced Turbine inlet at 500°C similar to Waste Heat Recovery applications
- Single compressor configuration
- Provides Steady & Transient Cycle Performance Data used to predict RCBC performance and operations

Recompression Brayton Cycle (RCBC)



Objectives

Demonstrate high performance cycle with parallel compressors & multiple HEX

- Increase Turbine inlet to 715°C
- Measure Steady & Transient Cycle Performance Data, evaluate operability
- Demonstrate pathway to 50% thermal efficiency
- Supports application to in-direct coal, HT WHR Industrial sources, and CSP plants

STEP Project Status

- Site Construction Progress Excellent
  - Building Occupancy received in early June 2020 on schedule
  - Process Electrical, Primary Heater, Cooling Water, Compressor Installation progressing
- Significant Achievements on Major Equipment Design & Fabrication
  - Most Major Equipment delivered or near completion
  - Equipment deliveries to site started in Nov 2019 and new arrivals every month
- Challenges with ‘first of a kind’ low TRL equipment
  - High Temperature Recuperator Design Life
  - Fabrication of Turbomachinery, Primary Heater Fabrication, and Turbine Stop Valve
  - Resolved technical issues and progressing with final equipment manufacture and delivery
- Developing supply chain for new materials and large-scale equipment
- Installation of equipment on-going with commissioning starting in Spring 2022

STEP Demo Objectives – Technology Maturation

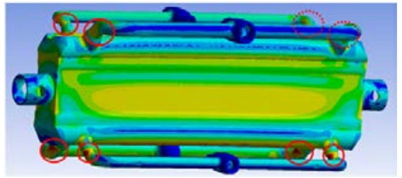
STEP DEMO

INDIRECT-FIRED CYCLE

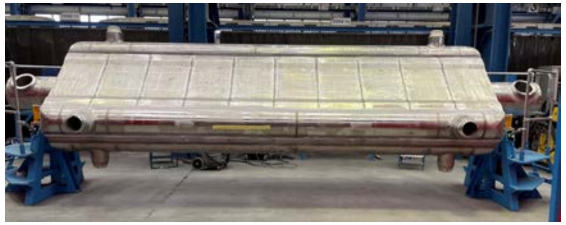
Recuperator Development

Compact, high efficiency designs for high T, high diff. pressure sCO_2

High Temperature Recuperator meets performance and life



High Temperature Recuperator fabrication nearing completion



INDIRECT-FIRED CYCLE

Turbine Technology

Low leakage seals, bearings; high temp, high power density sCO_2 turbine designs

Compact turbine assembly operates at >700°C

INDIRECT-FIRED CYCLE

Materials

Development of compatible materials for high T sCO_2 conditions

First large-scale complex Inconel 740H tube heat exchanger

Heater coil operates at 265 bar and 700°C

INDIRECT-FIRED CYCLE

Materials

Development of compatible materials for high T sCO_2 conditions

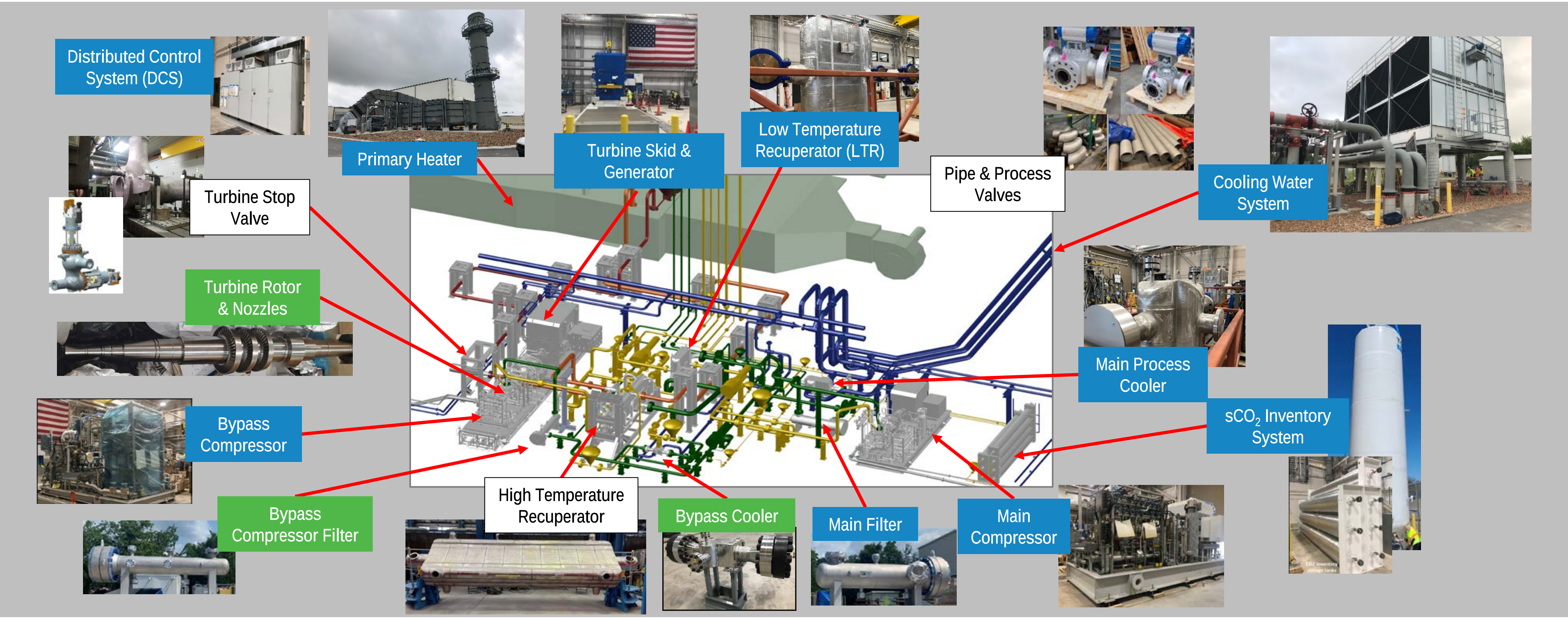
Large-scale Cast Haynes 282 Turbine Stop Valve fabrication

Turbine Stop Valve operates at 265 bar and 700°C

Advance state of the art for high temperature sCO_2 power cycle performance from Technology Readiness Level 3 to 7

NATIONAL ENERGY TECHNOLOGY LABORATORY gti SwRI

Process Equipment in Test Building



Blue – Received and Set, Green – Received, White – In Fabrication

Timeline to Test Operations

- **Jan. 2022** — Complete Key Equipment deliveries
- **May 2022** — Mechanical Completion – Simple Cycle
- **Sep. 2022** — Complete Commissioning Simple Cycle
- **Dec. 2022** — Complete Simple Cycle Tests
- **Apr. 2023** — Complete RCBC Reconfiguration
- **Dec. 2023** — Complete RCBC Tests (End Project)

STEP Test System Modeling

	Steady State	Transient
Software	Aspen Plus, Flownex	Flownex
Property Method	NIST REFPROP	NIST REFPROP
Cases Analyzed	2 Simple Cycle, 7 RCBC	Various operating scenarios such as start up, shut down, trips, and load level changes for both configurations
Purpose	Results used to define equipment requirements and specifications	Results supported system requirements and operational analysis of facility

Data generated will be used to validate the steady state and transient models, which will be used to project performance at the commercial scale and be valuable tools for other sCO_2 systems in the future

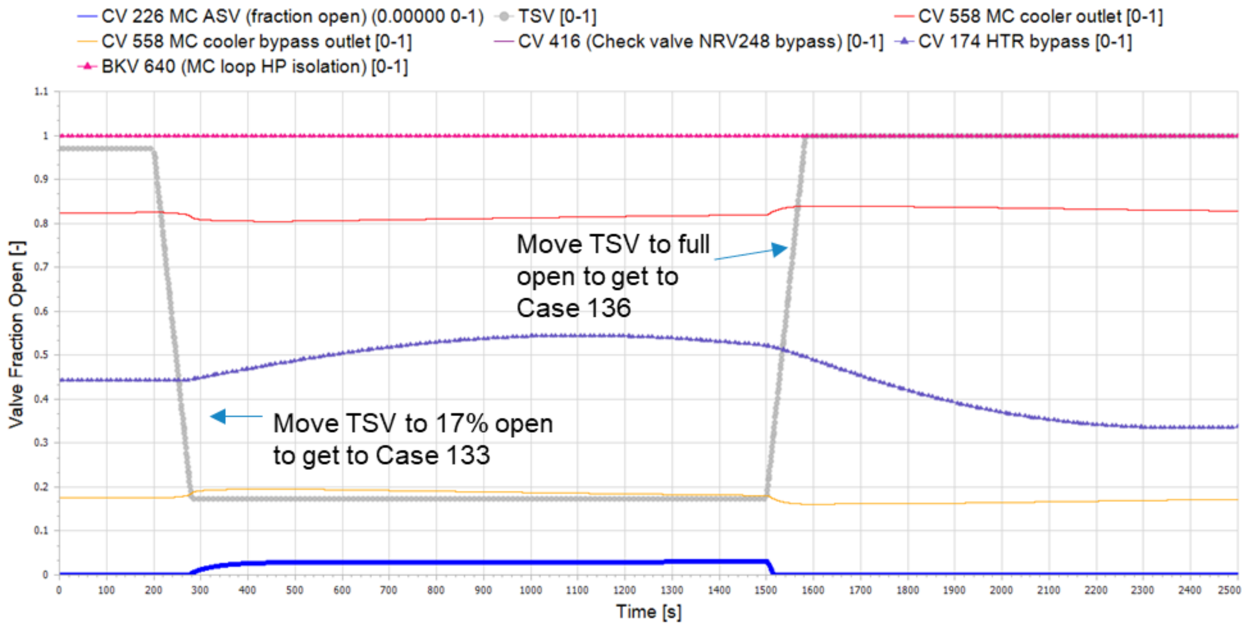
Steady State Modeling Initial Results

Model Names	Cycle Configuration	Description	Load %	Net Power Level (MWe)	Cooler Exit Temperature	Turbine Inlet Temperature	Cycle Efficiency
133	Simple	Simple cycle minimum load case	Min	2.5	35°C	500°C	22.6%
136	Simple	Simple cycle maximum load case	Max	6.4	35°C	500°C	28.3%
151	Recompression	Baseline case	100%	10.0	35°C	715°C	43.4%
152	Recompression	"Hot" Day Case	70%	6.6	50°C	675°C	37.4%
153	Recompression	"Cold" Day Case	100%	9.9	20°C	525°C	36.8%
154	Recompression	Partial load case using inventory control	40%	4.0	35°C	715°C	37.0%
155	Recompression	RCBC at 500°C turbine inlet temperature	70%	6.9	35°C	500°C	32.5%
157	Recompression	Partial load case using TSV throttling (transient condition)	40%	4.2	35°C	715°C	30.8%
157a	Recompression	Partial load case using TSV throttling	40%	3.9	35°C	675°C	29.6%

Simple Cycle Power Level Transient Sample Results

> Max Load (6.4 MWe) → Min Load (2.5 MWe) → Max Load (6.4 MWe) by throttling the Turbine Stop Valve (TSV)

- TSV (gray line) closes to 17% open at 200s and reopens fully at 1500 seconds
- As a result:
  - The HTR bypass valve (purple triangle) opens to maintain a 7°C approach temperature to protect the HTR
  - The 3-way valve of the cooler (red and yellow lines) adjusts flow through and around the cooler to maintain a 35°C inlet temperature to the MC
  - The ASV opens slightly to allow minimal recycle

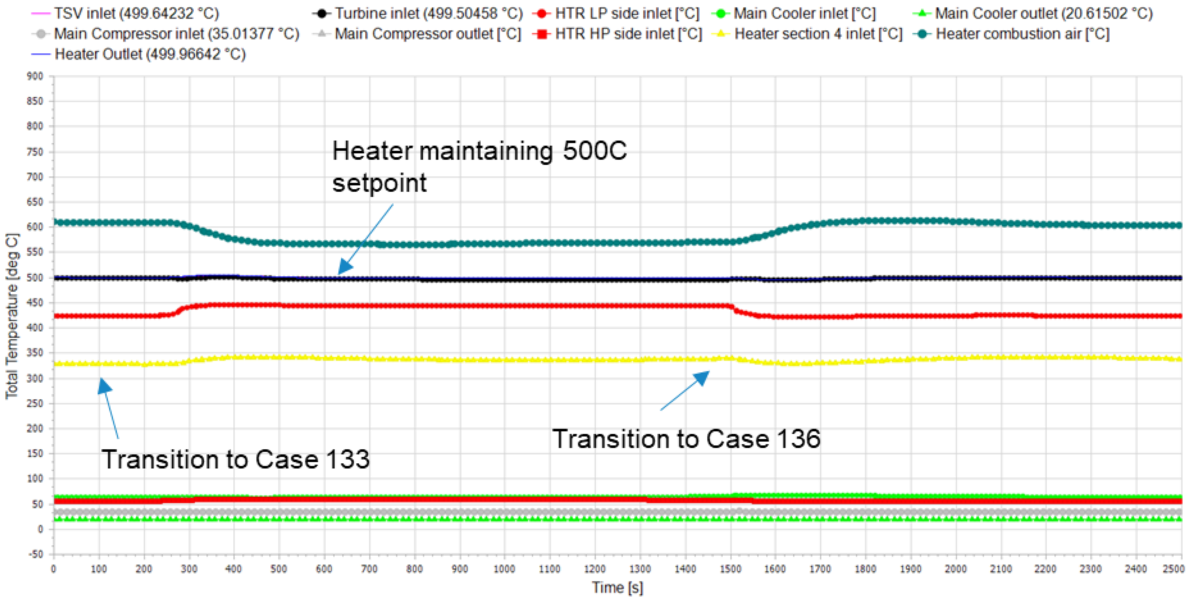


TSV = Turbine Stop Valve
ASV = Anti-surge valve
MC = Main Compressor

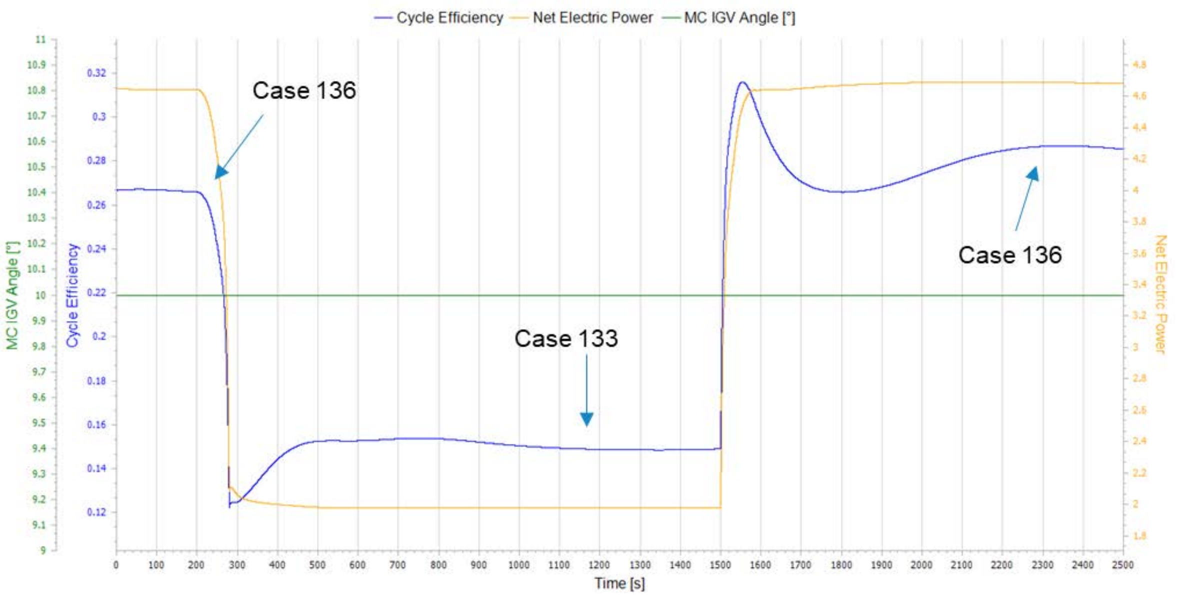
HTR = High Temperature Recuperator
HP = High pressure

Simple Cycle Power Level Transient Sample Results

> Impact on system temperatures
> Most temperatures remain relatively constant
> Heater maintaining a constant setpoint of 500°C turbine inlet temperature by adjusting heater combustion air temperature



> Impact on system performance
> Cycle efficiency (blue) & net electric power (yellow)
> After the adjustment of TSV at 200 and 1500 seconds, system takes 200 – 600 seconds to settle out



Transient Modeling Key Findings

- Control valve schedules during start-up were evaluated and determined
- Sequence approaches to manage component temperatures within specification
- Determined timing to enable heater ignition/firing at minimum system flowrate.
- Determined if liquid formation occurs during loop filling.
- Determined start up and interactions of two parallel compressor loops for RCBC
- Evaluated fast ramp scenarios and identified limiting capabilities of other sub-systems
  - (e.g., liquid vaporizer capacity).

STEP Simulator

> A virtual simulator will be built of the facility

> Flownex will represent the hardware physics

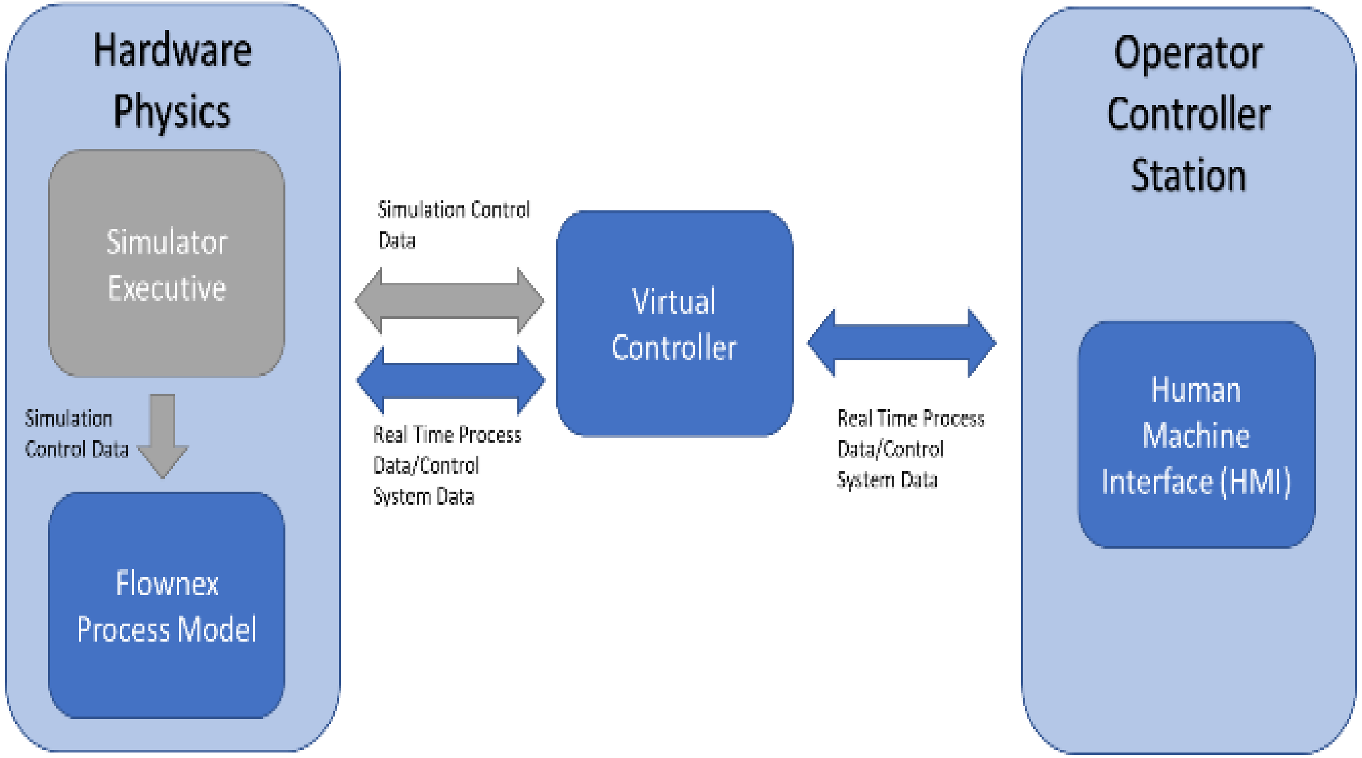
> Mark VI controller will be used for the virtual controller

> Operators will use this simulator

  – Training to gain familiarity with test system dynamics

  – Practice various control strategies

  – Assess “What if” scenarios



STEP Joint Industry Program

Leverage $115 MM in US DOE funding and ~$41MM in Industry funding to determine how this technology fits into your power generation plans and influence the project direction

Several levels of participation available to Industry:

1. **Steering Committee Level**
   - Input and advisory recommendations to the project team
   - Direct participation in bi-monthly advisory meetings
   - Attendance at bi-annual technical interchange meetings
   - Receipt of quarterly technical status reports
   - Access and use of Project System Data
   - Opportunity for facility visits and training in system operations
   - Period of exclusive access to license system IP
2. **Associate Membership**
   - Attendance at bi-annual technical interchange meetings
   - Receipt of quarterly technical status reports
   - Opportunity for 2 site visits per year
3. **Alternative member arrangements can be discussed.**

Project team welcomes new individual or joint participants to the Joint Industry Program!

Summary & Conclusions

- STEP Facility Significant Progress on Major Equipment Fab/Installation
- Maturing low TRL equipment & educating industry engineers and supply chain
- Models of System Operation in Simple and RCBC configurations completed
- Digital Simulator under development to train operators & potential commercial power generation system developers
- Commissioning to Initiate in Spring 2022 to start technology demonstrations

STEP Project Status can be followed at *www.STEPdemo.us*

Gratefully Acknowledging the Support from U.S. DOE-NETL and Project Partners

This presentation was prepared by GTI as an account of work sponsored by an agency of the United States Government. Neither GTI, the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Questions?

Working with Industry and Governments to Build and Demonstrate Low-Cost, Low-Carbon, Efficient Energy Systems

STEP DEMO

FOR A BETTER ECONOMY AND A BETTER ENVIRONMENT

SUPPLY	CONVERSION	DELIVERY	UTILIZATION

RESEARCH & DEVELOPMENT

PROGRAM MANAGEMENT

TECHNICAL/ ANALYTICAL

CONSULTING

TRAINING

COMMERCIALIZATION

400+ EMPLOYEES

World-class piloting facilities headquartered in Chicago area

NATIONAL ENERGY TECHNOLOGY LABORATORY

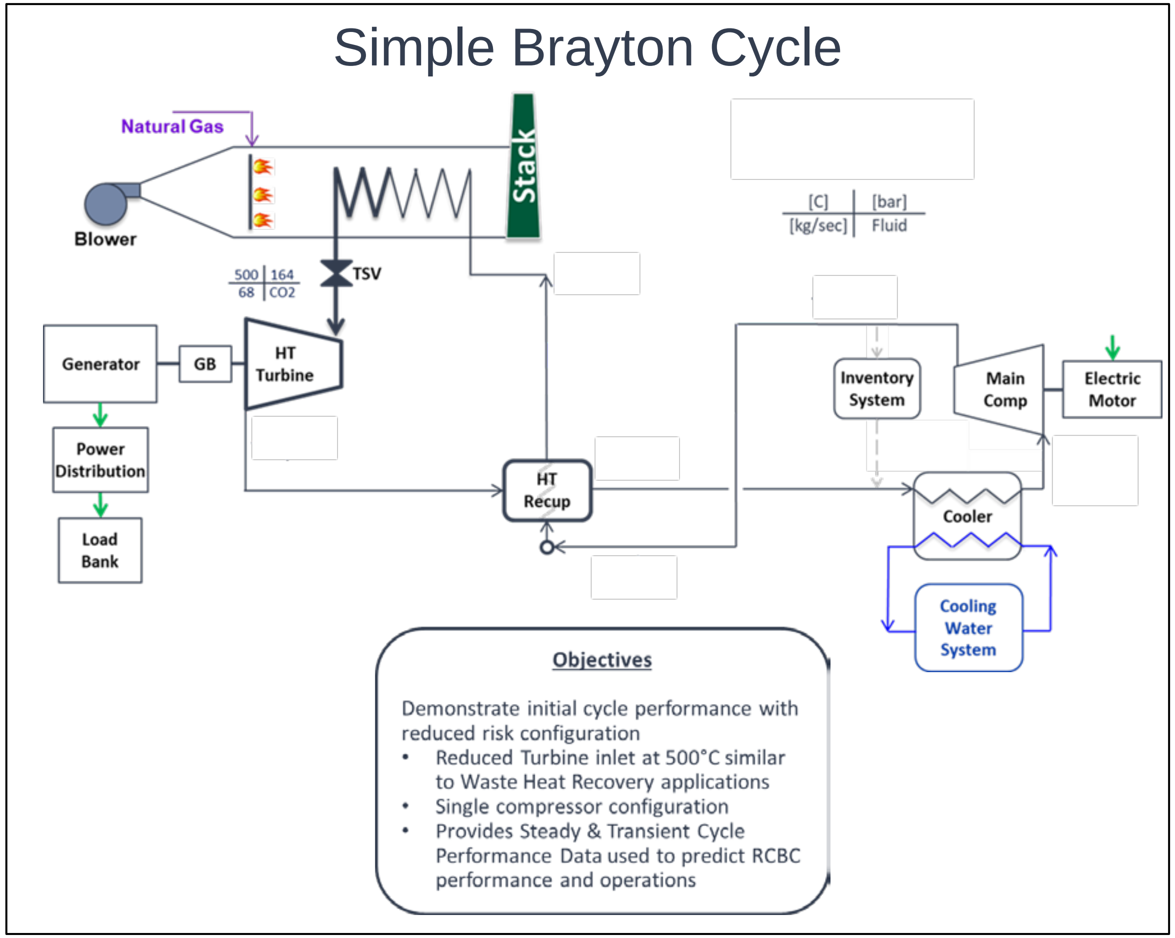
Back Up

Simple Cycle Test Objectives Per SOPO

> Objectives:

- Demonstrate basic operation and control of a simple recuperated sCO2 Brayton power cycle producing greater than 5 MWe.
- Implement and test an automated control system for the safe and predictable operation of the simple recuperated Brayton cycle through normal operating transients and simulated emergency transients.
- Obtain component performance data for sCO2 expander, recuperator, heat source, and compressor over a range of operating conditions to validate component performance predictions.
- Obtain cycle performance data to validate steady state and dynamic models and performance predictions.

This (simple cycle test) plan will verify the facility and component performance at lower temperatures (500°C) and in a configuration with reduced technical risk.

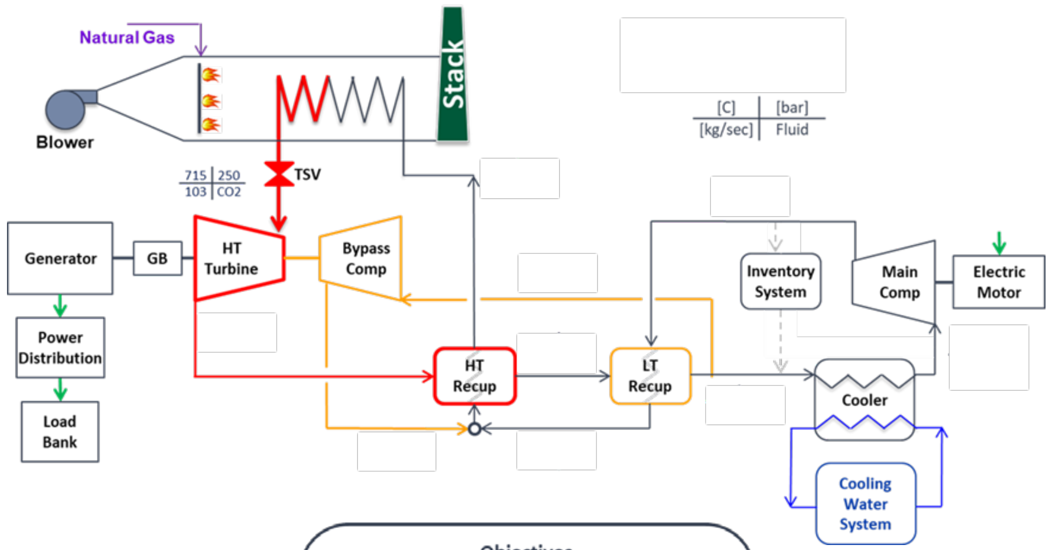


Recompression Closed Brayton Cycle (RCBC) Test Objectives Per SOPO

> Objectives:
  - Demonstrate basic operation and control of a RCBC power cycle producing 10 MWe.
  - Implement and test an automated control system for the safe and predictable operation of the RCBC through normal operating transients and simulated emergency transients.
  - Obtain component performance data for new and updated components over a range of operating conditions to validate component performance predictions.
  - Obtain cycle performance data to validate steady state and dynamic models and performance predictions.

This (RCBC) plan will verify the performance capability of the technology temperatures (715°C) and in a configuration with reduced technical risk.

Recompression Brayton Cycle (RCBC)



Objectives

Demonstrate high performance cycle with parallel compressors & multiple HEX
- Increase Turbine inlet to 715°C
- Measure Steady & Transient Cycle Performance Data, evaluate operability
- Demonstrate pathway to 50% thermal efficiency
- Supports application to in-direct coal, HT WHR Industrial sources, and CSP plants