The STEP 10 MWe sCO_2 Pilot Demo Status Update

Jeff Moore (SwRI) Project Manager

J. Marion (GTI Energy) Project Director

September 26, 2024

Agenda

1. Project overview
2. History & learnings getting to Mechanical Completion
3. 2024 activities
    a. Overall commissioning progress to date
    b. Test Results
    c. Outlook to complete SC commissioning
4. Future Plan
5. Summary

Why is it Important? sCO_2 Power Cycles Offer:

SOUTHWEST RESEARCH INSTITUTE

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

- Smaller "footprint" and lower construction costs
- Net plant efficiency improvement
- Reduction in LCOE (Levelized Cost of Electricity $/kWhr)
- Reduced fuel and water usage
- Reduced emissions

Improve power plant efficiency

Reduce costs, emissions, water use

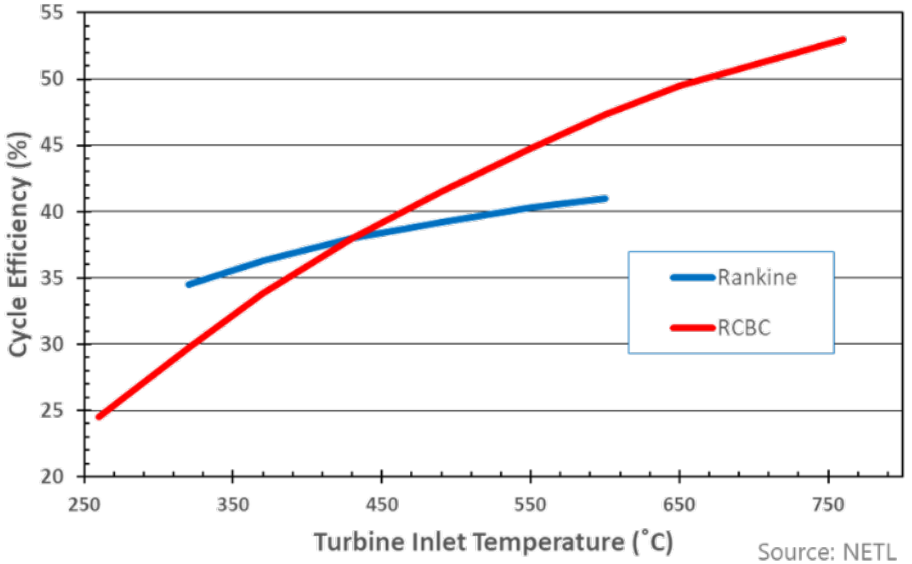
Compact: small size turbomachinery

Quick response time

Zero emissions configurations

Versatile technology with many applications

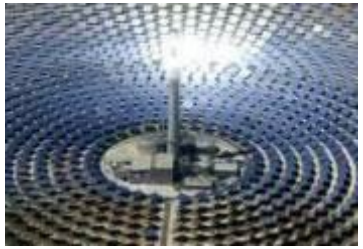
sCO2 has greater efficiency than steam Rankine cycle at high turbine inlet temperatures



Source: NETL

Versatile Technology – Broad Applicability

Waste Heat Recovery



Concentrated Solar

Energy Storage

Geothermal

Fossil Fuel & Biomass

Nuclear

STEP DEMO · NETL NATIONAL ENERGY TECHNOLOGY LABORATORY · GTI ENERGY · SwRI · GE VERNOVA

sCO_2 Cycles – Supports the Energy Transition

Potential USA Impact by 2050

SOUTHWEST RESEARCH INSTITUTE

Industrial Heat Pumps
10% of Industrial Heat
138 GW_{th} 970,000 GWh_{th}/yr
25.6 MM tpa CO_2

Small WHR
25% of SCGT Installed Base
9.3 GW_e 10,700 GWh_e/yr
4 MM tpa

Electro-Thermal Energy Storage
25% of Total Storage
40.9 GW_e 89,500 GWh_e/yr
33.6 MM tpa CO_2

Concentrated Solar
5% of Total Solar
14 GW_e 98,500 GWh_e/yr
37.0 MM tpa CO_2

Next Gen Nuclear
10% of Total Nuclear
8 GWe 62,500 GWh_e/yr
23.5 MM tpa CO_2

OxyFuel with CCS
10% of NG fueled generation
13.3 GW_e 93,100 GWh_e/yr
35 MM tpa CO_2

Adv Geothermal
10% of Geothermal
8.5 GW_e 60,000 GWh_e/yr
22.5 MM tpa CO_2

Path to Net-Zero

% = Assumed market penetration
GW_e or GW_{th} = installed capacity
GWh_e /yr or GWh_{th}/yr = energy delivered
MM tpa = million tonnes CO_2 per annum reduced
Primary data source: eia annual energy outlook

SwRI 2024

Total Potential
181.2 MM tpa CO_2
~12% of Current Electric Power Emissions

STEP DEMO NETL NATIONAL ENERGY TECHNOLOGY LABORATORY GTI ENERGY SwRI GE VERNOVA

Supercritical Transformational Electric Power (STEP) Demo Project

SOUTHWEST RESEARCH INSTITUTE

- $158.6 million project to design, construct, commission, and operate a 10 MWe sCO_2 demonstration power plant
- **Objectives:**
  - Advance sCO_2 power from TRL3 to TRL7
  - Demonstrate pathway to net plant efficiency > 50%
  - Demonstrate control and operability at 500°C and ≥700°C turbine inlet temperature with 10 MWe power generation
- **Project Partners:**

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY | GTI ENERGY | SwRI | GE VERNOVA

- **Industry Co-Funders:**

KEPCO KOREA ELECTRIC POWER CORPORATION | Natural Resources Canada / Ressources naturelles Canada / Canada | Southern Company | TEXAS COMMISSION ON ENVIRONMENTAL QUALITY | ENGIE | CSIRO | AMERICAN ELECTRIC POWER BOUNDLESS ENERGY | EGAT Power for Thai Happiness

www.STEPdemo.us

STEP Project Interest from around the world

SwRI
SOUTHWEST RESEARCH INSTITUTE

AURA

Énergie

Une turbine à CO2 de la taille d'une table peut alimenter 10 000 foyers

Rinnovabili.it
IL QUOTIDIANO SULLA SOSTENIBILITA' AMBIENTALE
DIRETTORE MAURO SPAGNOLO

ENERGIA · AMBIENTE · ECONOMIA CIRCOLARE · GREEN ECONOMY · MOBILITÀ · GREENBUILD

Home › Energia › Efficienza Energetica › Turbina a CO2 supercritica, inaugurato il maxi impianto pilota

Energia | Efficienza Energetica

Turbina a CO2 supercritica, inaugurato il maxi impianto pilota

Taglio del nastro in Texas per l'impianto dimostrativo Supercritical Transformational Electric Power da 10 MW. Hamilton (SwRI): "Cambierà il modo in cui pensiamo alla produzione di energia"

2 Novembre 2023

Modern Power Systems
COMMUNICATING POWER TECHNOLOGY WORLDWIDE

Home | News | Buyer's Guide | Features | Events | Jobs | Video | Advertise With Us | Company A - Z | White Paper

STEP forward for Brayton high efficiency demo

7 November 2023

Print | Email

GTI Energy and its partners, Southwest Research Institute (SwRI) and GE Vernova, have marked w they believe is a significant leap forward in energ technology advancement with the opening of the Supercritical Transformational Electric Power (ST Demo test facility in San Antonio, Texas. Funded the US Department of Energy and industry partne the STEP Demo facility is said to be a first-of-a-ki

CleanTechnica

A high tech supercritical carbon dioxide power plant is taking shape behind the walls of a mode building in Texas, with the potential to lower the cost of concentrating solar power systems.

A Tiny Supercritical Carbon Dioxide Turbine Can Power 10,000 Homes

SAN ANTONIO Report

Government | Business | Education | Environment | Health | Arts | Tech | Opinion | Live Like a Local

BUSINESS & DEVELOPMENT

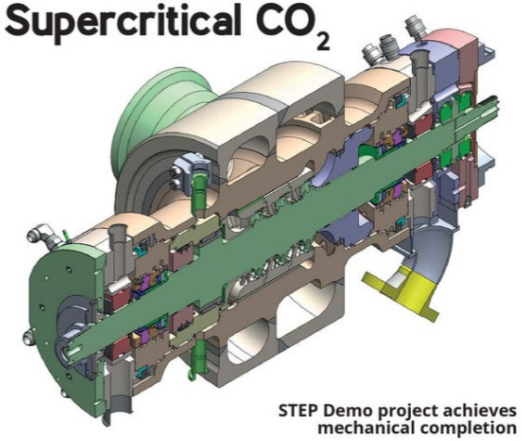
$155M demonstration plant at Southwest Research aims to revolutionize energy industry

19 USA focus: H2 hubs; gas with CCS; wildfire mitigation
26 Hydrogen economy: making it a reality
32 European offshore wind: immediate action needed
38 Piston power: optimising gensets to reduce emissions

MPS
modern power systems

Volume 43 | Number 9 | November/December 2023
www.modernpowersystems.com

Supercritical CO_2



STEP Demo project achieves mechanical completion

SAN ANTONIO BUSINESS JOURNAL

REAL ESTATE
Crane Watch

$155M facility could change power landscape

Email | Share | Share | Share | Tweet | Unlock URL | Print | Order Reprints

STEP DEMO | NETL NATIONAL ENERGY TECHNOLOGY LABORATORY | GTI ENERGY | SwRI | GE VERNOVA

TDI Colombia

ENERGY DAILY
the power of earth and beyond

CARBON WORLD

STEP Demo Plant Ushers in Next Era of Power Generation With sCO2 Technology

EnergyPortal.eu

GAS | NEWS | NUCLEAR | SOLAR | WATER

The Future of Power Generation: Supercritical Carbon Dioxide

By Daniel Hall
OCT 27, 2023

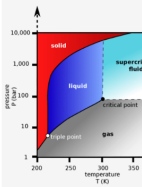
POWER Engineering

Emissions

GTI, KEPCO collaborating on supercritical CO2 power cycle rese

GTI and KEPRI will explore opportunities for joint research and development on sCO2 technologies over the next five years.

Clarion Energy Content Directors



(Editor's Note: This story originally published on May 2).

The non-profit research organization Gas Technology Institute and a unit of Korea Electric Power Co. (KEPCO) have signed an agreement to jointly research and develop supercritical carbon dioxide (sCO_2) power cycle technologies that could impact power generation efforts.

The memorandum of understanding between GTI and Korea Electric Power Research Institute (KEPRI) focuses on sCO_2 work which can lead to the potential for higher power conversation efficiencies and more compact turbomachinery. Such achievements could help lower capital costs and reduce plant footprints for power generators.

GTI and KEPRI will explore opportunities for joint research and development on sCO_2 technologies over the next five years. The partners will cooperate, share technical information, and potentially exchange research staff for

sCO_2 technology development and commercialization.

Zelosos por Buenas Renovables
¡Energía sostenible ahora!

SIN CATEGORÍA | XBO | XFR | XHU | XIT | XTR

La revolución de la tecnología de dióxido de carbono supercrítico (sCO2)

Por Enrique Gánem Corvera
OCT 27, 2023

STEP Project Milestones

SOUTHWEST RESEARCH INSTITUTE

BP1 | BP2 | BP3

- **2016 - Oct** — Project Start
- **2018 – Oct** — Ground-breaking
- **2019 - Jan** — Facility design complete
- **2020 - May** — Building Completed
- **2023 - Oct** — Mechanical Completion
- **2023 - Dec** — 1st Turbine Spin
- **2024 – Jan** — 1st Closed-Loop Test
- **2024 - Sept** — Simple Cycle Testing to be completed
- **2025-26** — RCBC Testing to be completed

STEP groundbreaking – Oct 2018

STEP site construction – Oct 2019

Building Foundation – Dec 2019

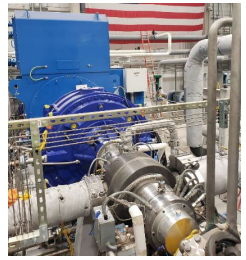
Certificate of Occupancy – May 2020

Mechanical Completion & Start of Commissioning – Oct 2023

Turbine & compressor install – Sep 2021

Compressor Commissioning

Turbine Test



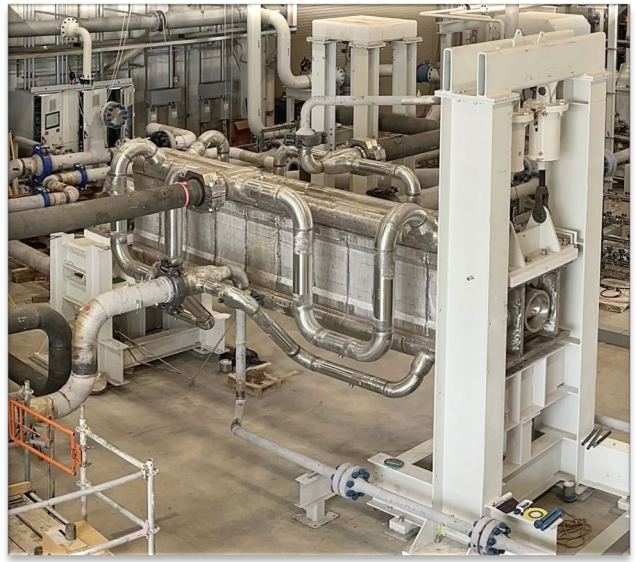
STEP DEMO | NETL NATIONAL ENERGY TECHNOLOGY LABORATORY | GTI ENERGY | SwRI | GE VERNOVA

STEP Demo Objectives – Technology Maturation Notable Achievements

SOUTHWEST RESEARCH INSTITUTE

High temperature recuperator (HTR)

- World's largest high temperature printed circuit heat exchanger (PCHE)
- 50 MWth and ~50 tons (~45,300 kg)



sCO2 turbine

- At ~1/10 the size of an equivalent steam turbine, is one of the world's highest power density for a terrestrial turbine
- 20,000 horsepower produced by 180 lb rotor (111 HP/lb)

Heater

- World's largest high temperature Inconel heater tube bundle
- 93 MWth

Turbine stop valve

- World's largest high temperature Haynes 282 casting
- 9,250 lbs (4196 kg)

STEP DEMO NETL NATIONAL ENERGY TECHNOLOGY LABORATORY GTI ENERGY SwRI GE VERNOVA

STEP Test Facility 2024

SOUTHWEST RESEARCH INSTITUTE

Now built, is being commissioned, and will complete BP2 intermediate temperature testing in 2024

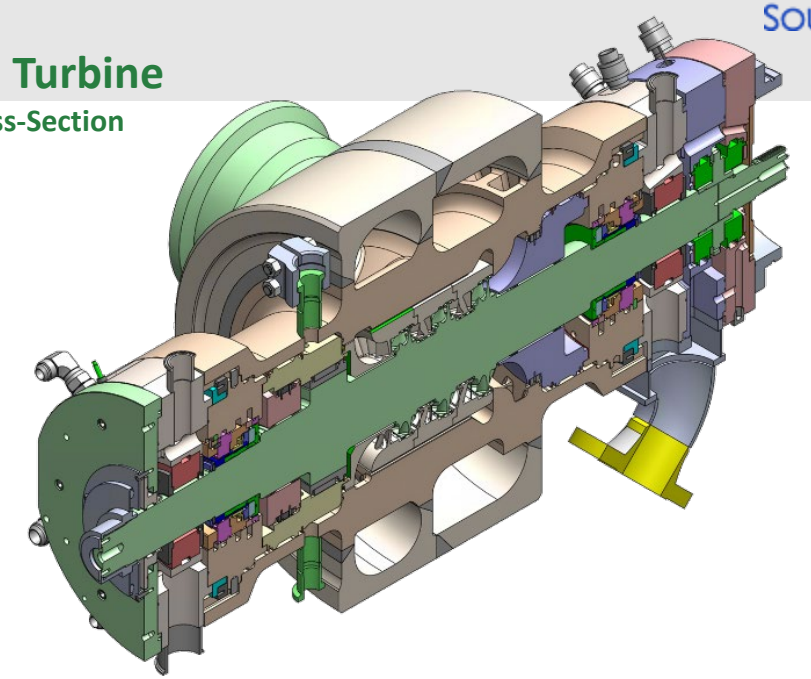
STEP Turbine

SOUTHWEST RESEARCH INSTITUTE

- 16 MWe gross
- T_{IT} 715°C, 250 bar sCO_2
- Three stage gas path
- Monolithic Nimonic 105 rotor
- Enhanced thermal gradient region
- Increased performance inlet/exit volutes
- Builds on successful SunShot 1 MWe demonstration [700°C]

Design basis from successful SunShot 1 MW_e pilot [715°C, 27,000 rpm]

STEP Turbine
Cross-Section



EDM of Turbine Stator

3-stage Monolithic Turbine Rotor

STEP Turbine Design Conditions

SOUTHWEST RESEARCH INSTITUTE

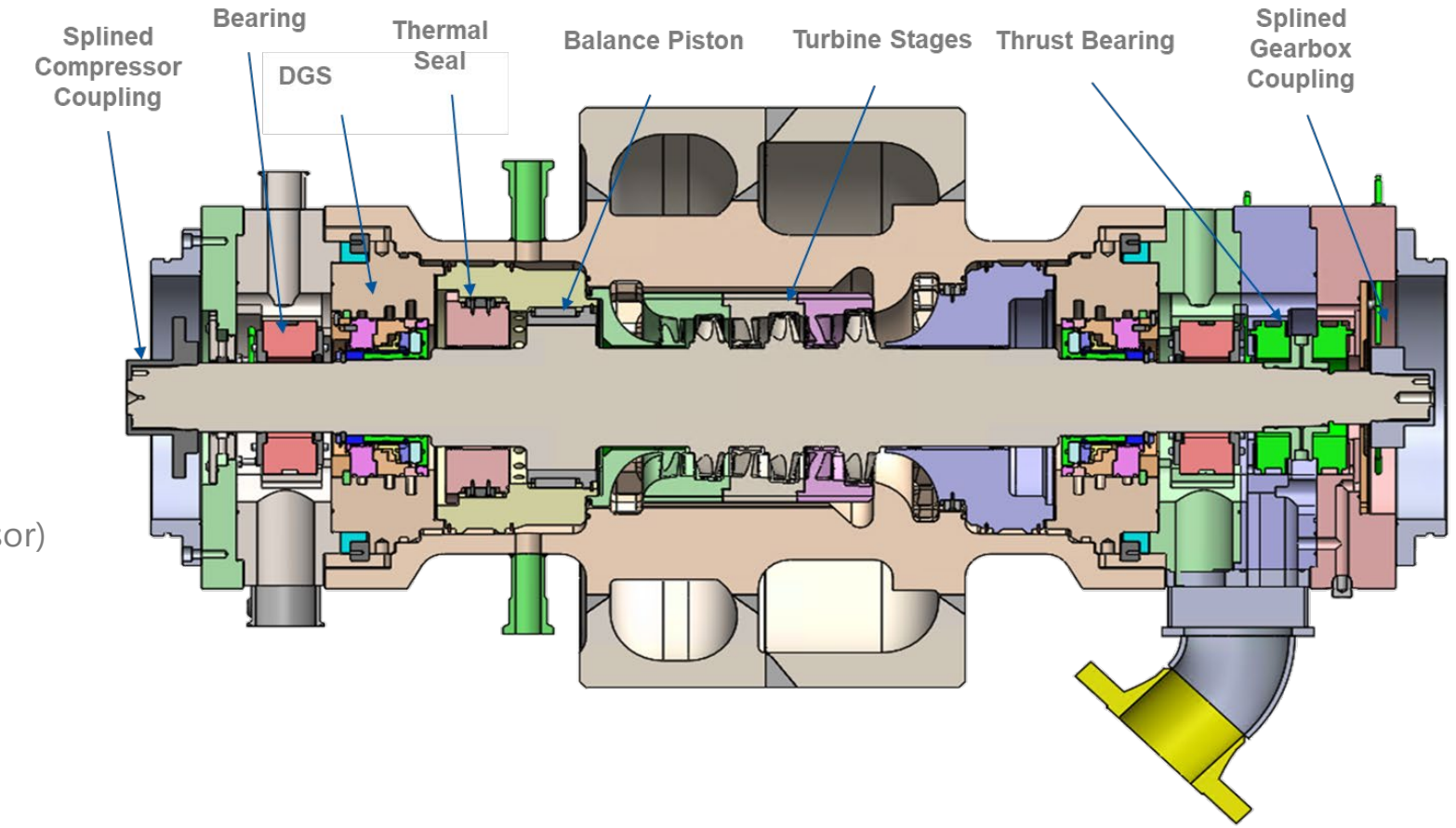
Inlet Flow
3,626 psi at 1,319°F (250 bar at 715°C)
227.4 lbm/s (103.2 kg/s)
Single Inlet – 5" Grayloc™ Flange
Velocity – 210.8 ft/s (Mach #: 0.12)

Exit Flow
1,307 psi at 1,086°F (90 bar at 586°C)
223.9 lbm/s (101.7 kg/s)
Single Exit – 6. Grayloc™ Flange
Velocity - 298.6 ft/s (Mach #: 0.20)

Rotor
Design Speed: 26,640 rpm
Max Continuous: 28,350 rpm
16 MW (13 MW Generator and 3 MW Compressor)

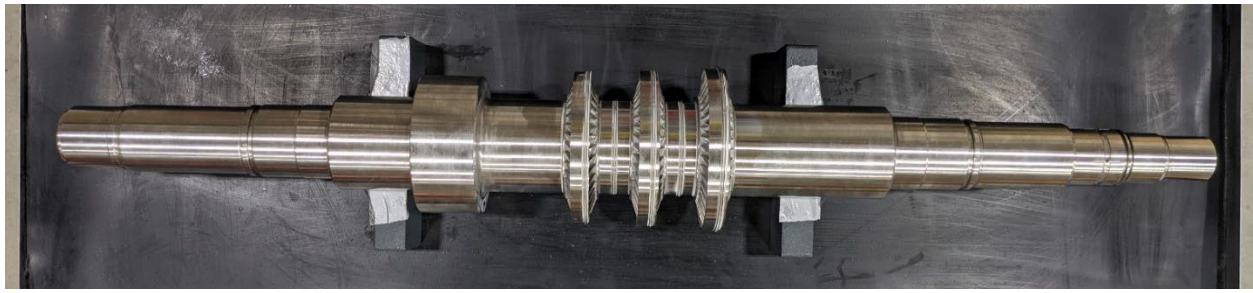
Case
Two design conditions
Inlet: 4,130 psi at 1330°F (285 bar at 721°C)
Exit: 2,600 psi at 1150°F (179 bar at 621°C)

Life
Creep Rupture: 100,000 hr. (with IN740H case)
Embrittlement: 2000 hr. (with IN625 case as built>600C)
Low Cycle Fatigue: 11,000 cycles



Rotor Manufacturing

- Nimonic 105 heat treated forging
- Airfoil shapes cut using a 5-axis electrode discharge machining (EDM)
- Different shops used for rotor final machining, grind, spline cutting, and balance
- Spline test piece made and trial fit

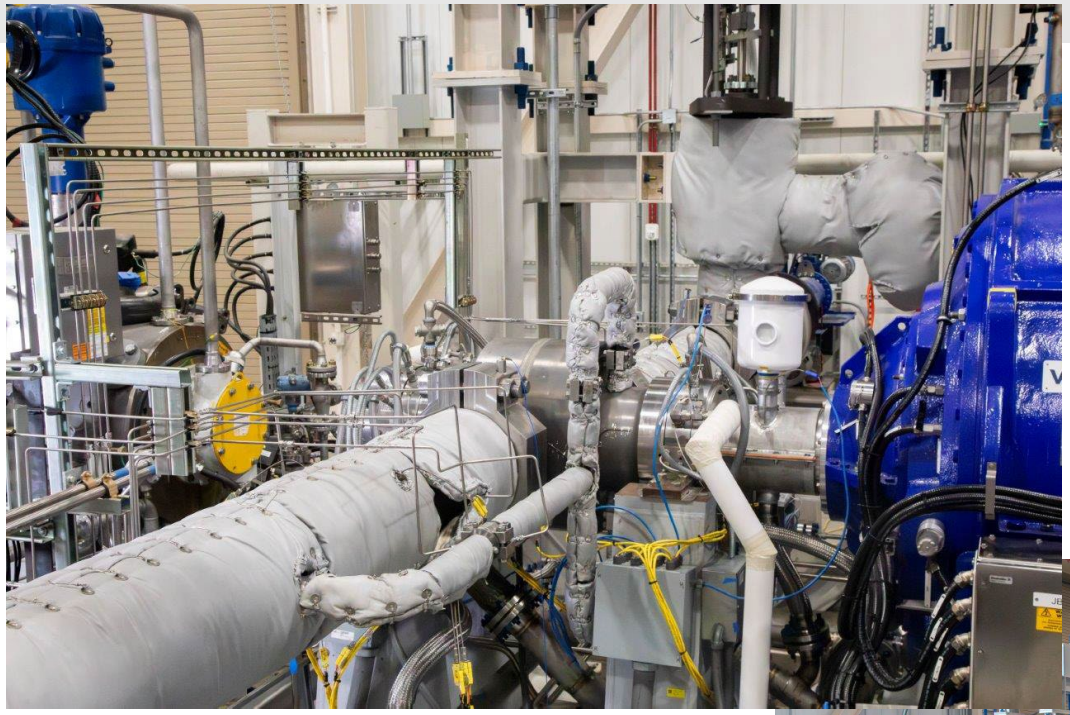


Turbine rotor following rough machining and EDM

Close up of EDM Turbine Blades with Spline Test Piece

Turbine Assembly

Fully Assembled STEP Turbine Skid



LT Turbine Stop and Control Valve

SOUTHWEST RESEARCH INSTITUTE

- Low Temperature [LT] valve rated for 550°C
- 2 valves in one
- Control valve for speed and load control
- Stop valve for ESD
- Both with 200 ms closure time to prevent overspeed due to sudden loss of load

STEP Compression System

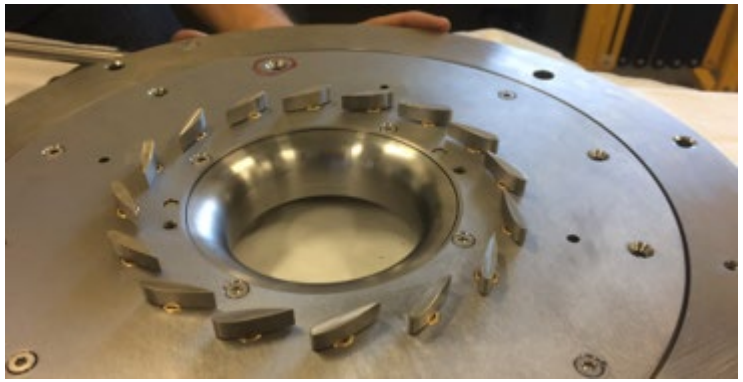
- Main Compressor electric motor driven
- Bypass Compressor directly driven by STEP sCO2 turbine
- Smallest BHGE radial impeller of class
- Compact Integral Guide Vanes (IGV) with large angle variation
- Wide testing operating range
- Baker Hughes OEM
- Received Dec 2020, Installed Sept 2022, Main compressor commissioning Nov'22– Feb'24
  - Accumulated 130 total starts, 250 hours of rotation

Design basis from industrial CO2 compressors and DOE Apollo project DE-EE-0007109

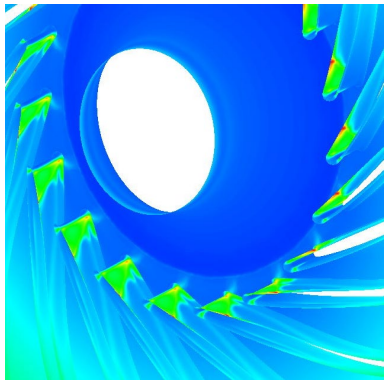
Main Compressor system and drive

Main compressor impeller

By-pass compressor impeller

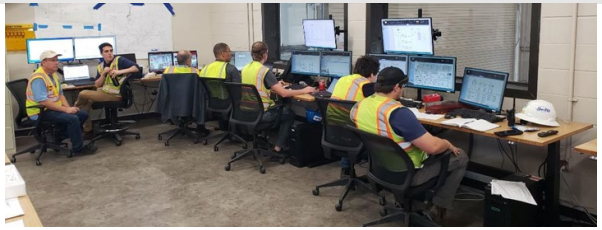


Inlet Guide Vanes (IGV)



IGV flow modeling

Commissioning Tests - August Update



Test ID	Description	Turbine speed, TiT	Completion Date
T-1	Warm-up	0 rpm, cold flow	Completed in December week of 12/18/2023
T-2	Loop Fill & Warm-up	0 rpm, cold flow	
T-3	ESD and overspeed trip check	5k rpm, cold flow	
T-4	Fill to supercritical state	0 rpm, cold flow	Week of 1/8/2024 and 2/8/2024 operation. Cold vents have been tuned and are ready for higher temperature operation.
T-5	Seal break-in, trim balance	12k rpm, cold flow	
T-6	Cold limited speed hold	12k rpm, cold flow	
T-7	Heater light-off (Limited speed turbine operation)	12k rpm, 200C	
T-8	Warm speed ramp to 18k RPM	18k rpm, 200C	
T-9	Temperature ramp to 400C	18k rpm, 400C	Completed 9/11

Commissioning Tests - August Update

SOUTHWEST RESEARCH INSTITUTE

- **Simple Cycle Min - Full speed 26,620 rpm at 500 ºC TiT and 3.6 MW turbine power achieved to date**

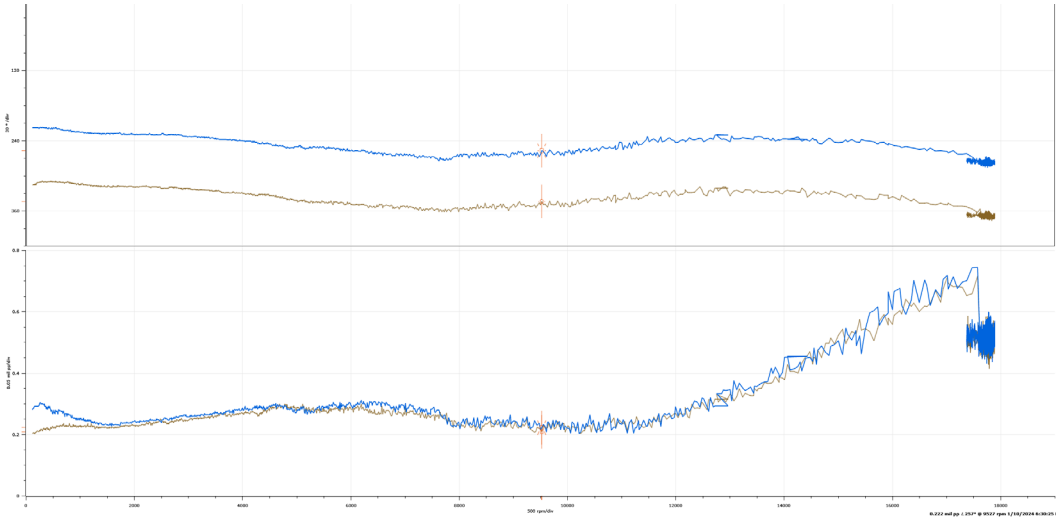
Test ID	Description	Turbine speed, TiT	Completion Date
T-10	400C Speed Ramp to 18kRPM	18k rpm, 400C	Completed 9/11
T-11	Full Speed No Load (FSNL)	26.6k rpm, 400C	Completed 9/11
T-12	Generator Connection and Initial Loading	26.6k rpm, 400C	Completed 9/12
T-13	Initial Load Ramp	26.6k rpm, 400C	Completed 9/13
T-14	Generator Synchronization	26.6k rpm, 400C	**Early / Mid October**
T-15	Simple Cycle Min	26.6k rpm, 500C	Completed 9/13
T-16	Simple Cycle Max	26.6k rpm, 500C	**Early / Mid October**
T-17	Loaded Trip	26.6k rpm, 500C	Completed 9/13

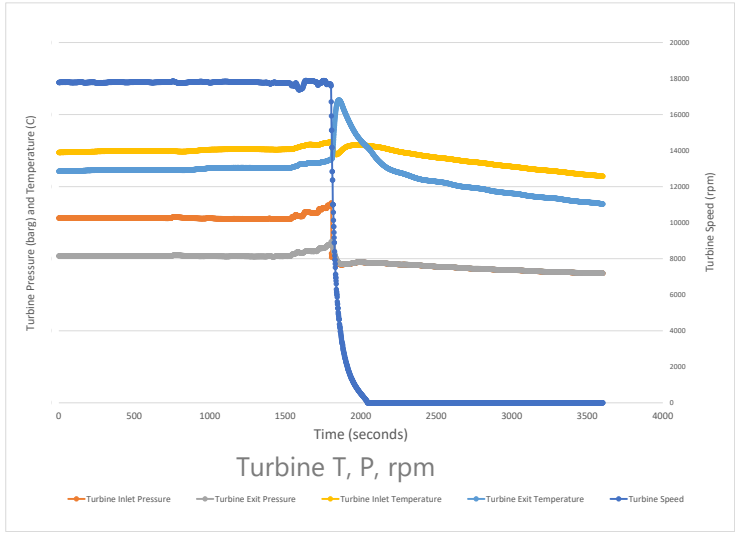
*Tested at 280C

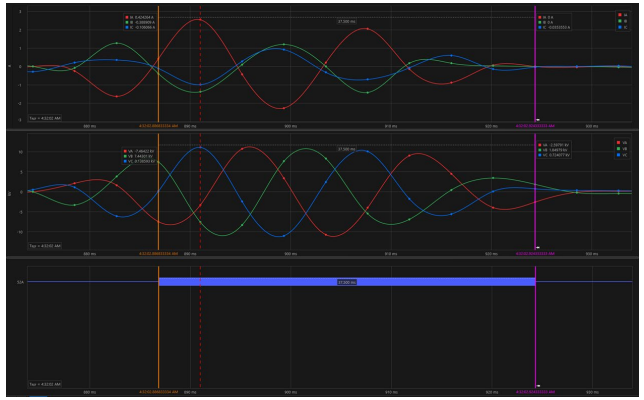
Turbine First Full Speed Test with Power Generation

SOUTHWEST RESEARCH INSTITUTE

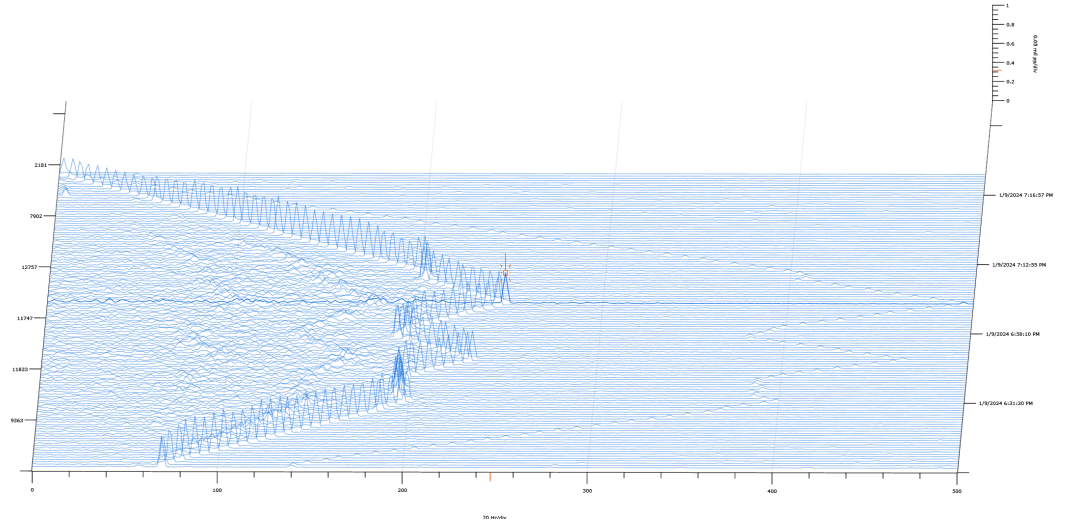
- Turbine inlet temperature of 280°C and speed of 27 krpm achieved in May 2024
- Low vibrations and critical speed response
- Speed and temperature control operational
- First power produced







Generator output



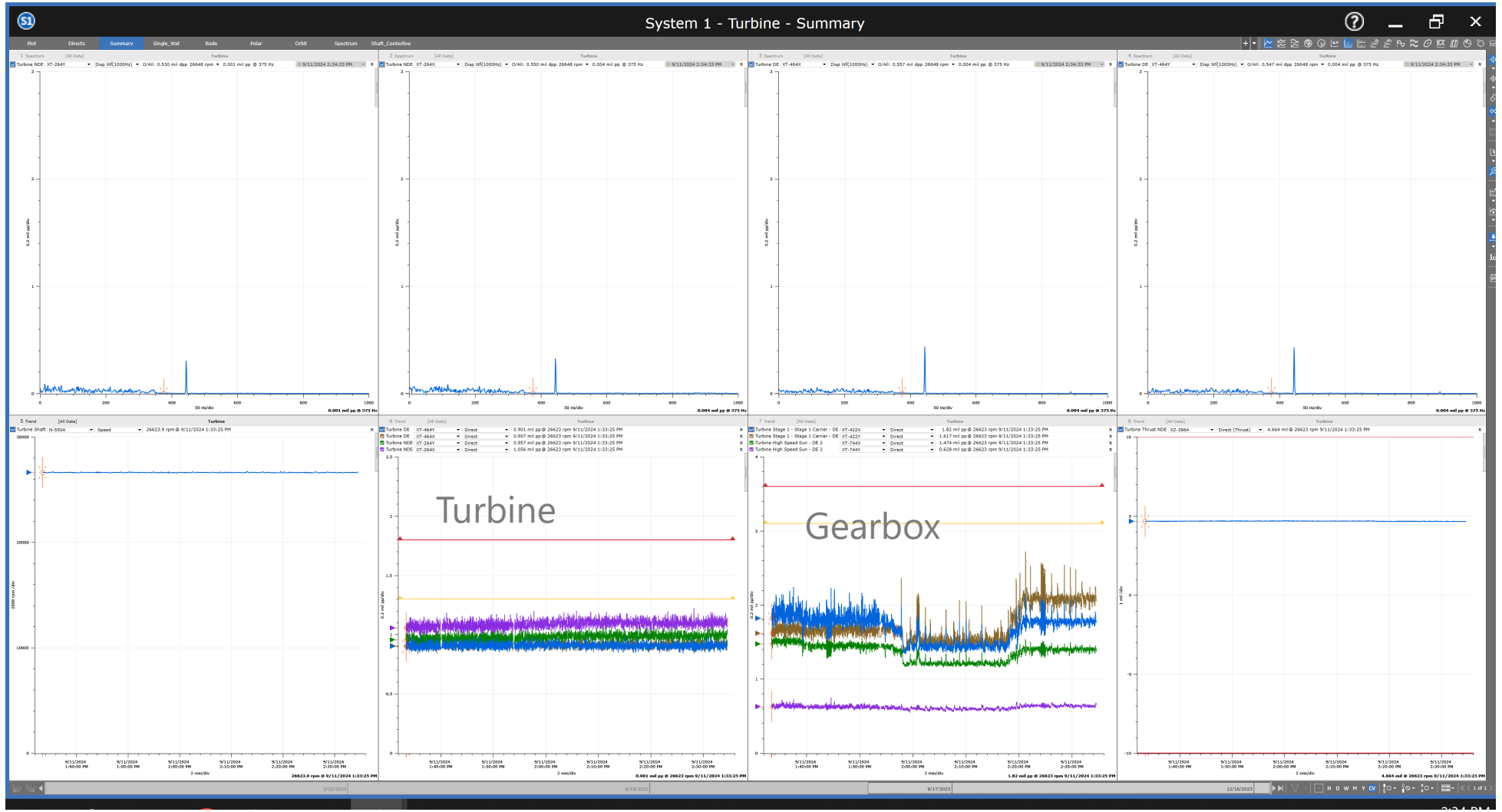
Simple Cycle Turbine Temperature Trend

SOUTHWEST RESEARCH INSTITUTE

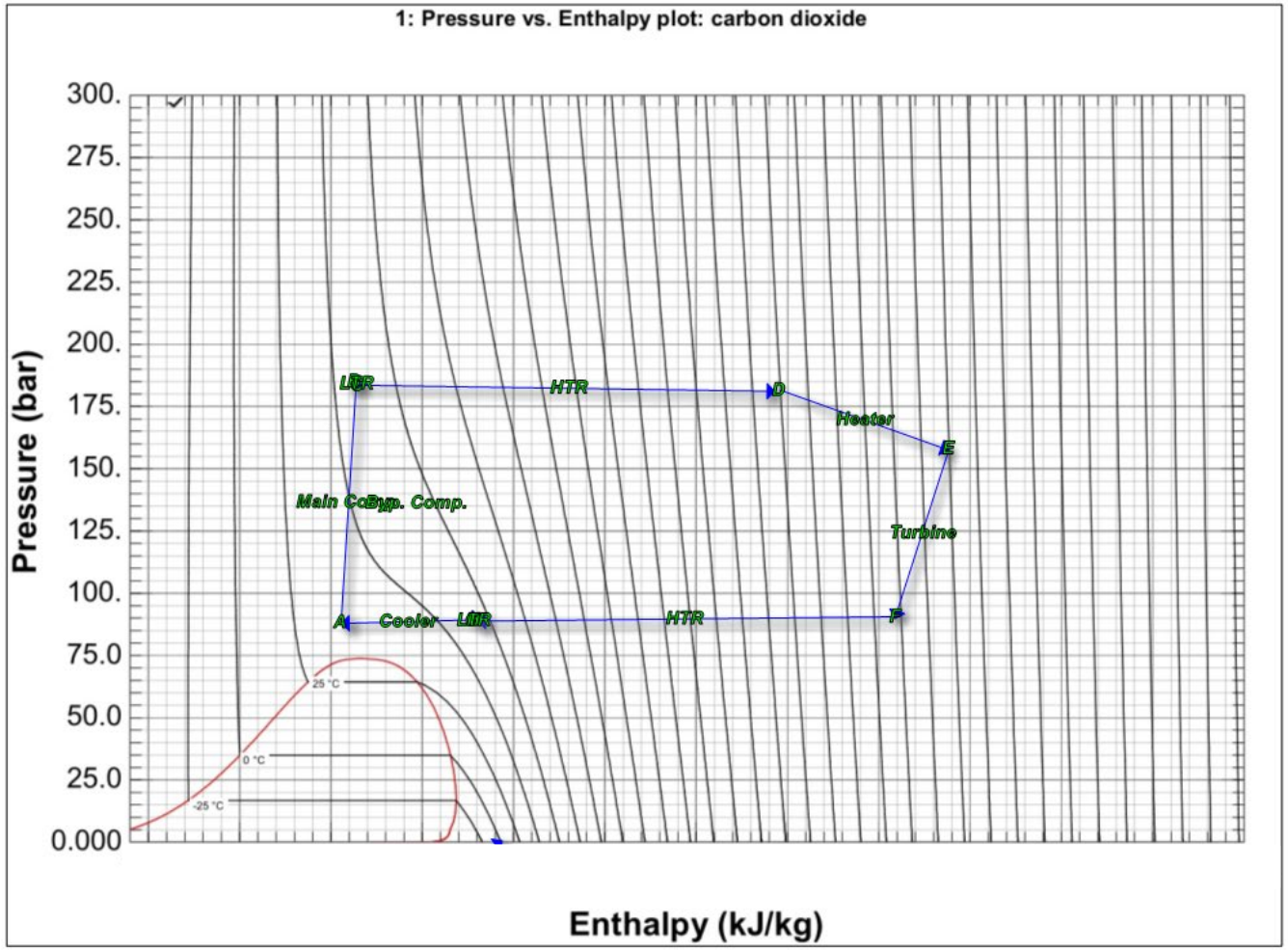
September 2024 Testing

Gross Turbine Power = 3.6 MW
Net Power Plant Output = 1.9 MWe

Turbine Train Vibration Trend



P-H Diagram of Power Cycle for Simple Min



A - Main Compressor Inlet
B - Main Compressor Outlet
C - HT Recup HP Inlet
D - Heater Inlet
E - Turbine Inlet
F - Turbine Outlet
G - LT Recup LP Inlet
H - MC Cooler Inlet

STEP Stop/Control Valve

- Supplier – GE Vernova (US)
- Haynes 282 material for 715°C
  - leveraged development under DOE AUSC program
- Advanced seals leveraging GE/Baker Hughes O&G capability
- Self-contained actuators leveraging GE/Baker Hughes O&G experience


GE Seal & shaft testing

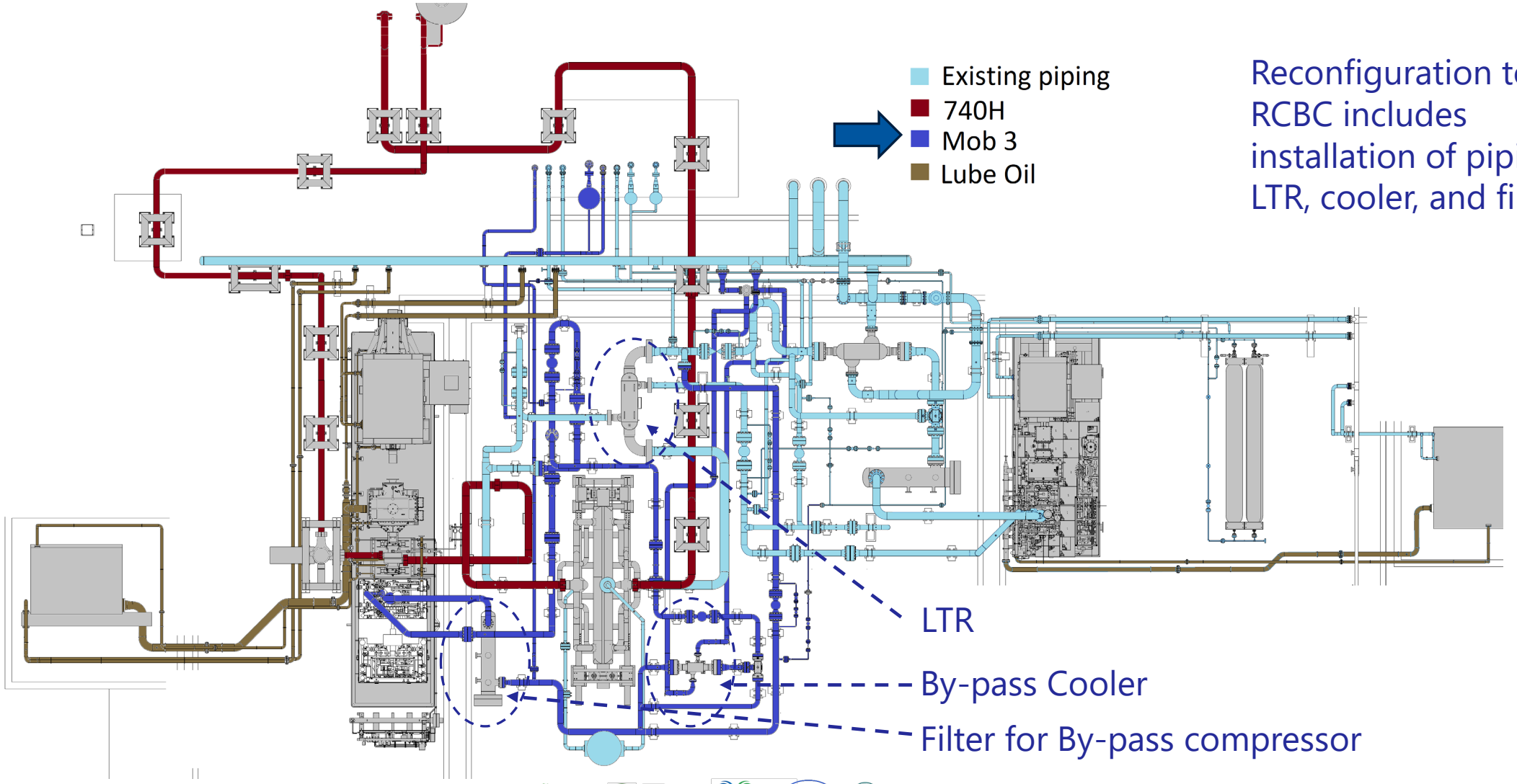
Valve design similar to conventional steam valves with sCO_2 specific differences addressed with analysis and testing


Machining valve body

Three ladle pour of main valve body

BP3 [RCBC Configuration]

SOUTHWEST RESEARCH INSTITUTE



Reconfiguration to RCBC includes installation of piping, LTR, cooler, and filter

Summary and Outlook

SOUTHWEST RESEARCH INSTITUTE

- **sCO2 power cycles are versatile to heat source and application and provide performance AND cost benefits over steam cycles**
- **Technology maturation by the STEP Pilot Demo project provides path to future commercial systems with higher efficiency and lower emissions**
- **STEP facility is now built and operating**
  - Achieved Simple-Min Conditions (500°C and 3.6 MW turbine power)
- **STEP (Simple Cycle - 500°C – BP2) test operations are completing 2024**
- **STEP (RCBC - 715°C – BP3) Planned for 2025-26**

Keep up to date on STEP Project progress at *www.STEPdemo.us*

Gratefully Acknowledge the Support from U.S. DOE and Project Partners

www.STEPdemo.us