STEP DEMO

Supercritical CO_2 Power Cycles Symposium

The STEP 10 MWe sCO_2 Pilot Installation and Commissioning Status Update

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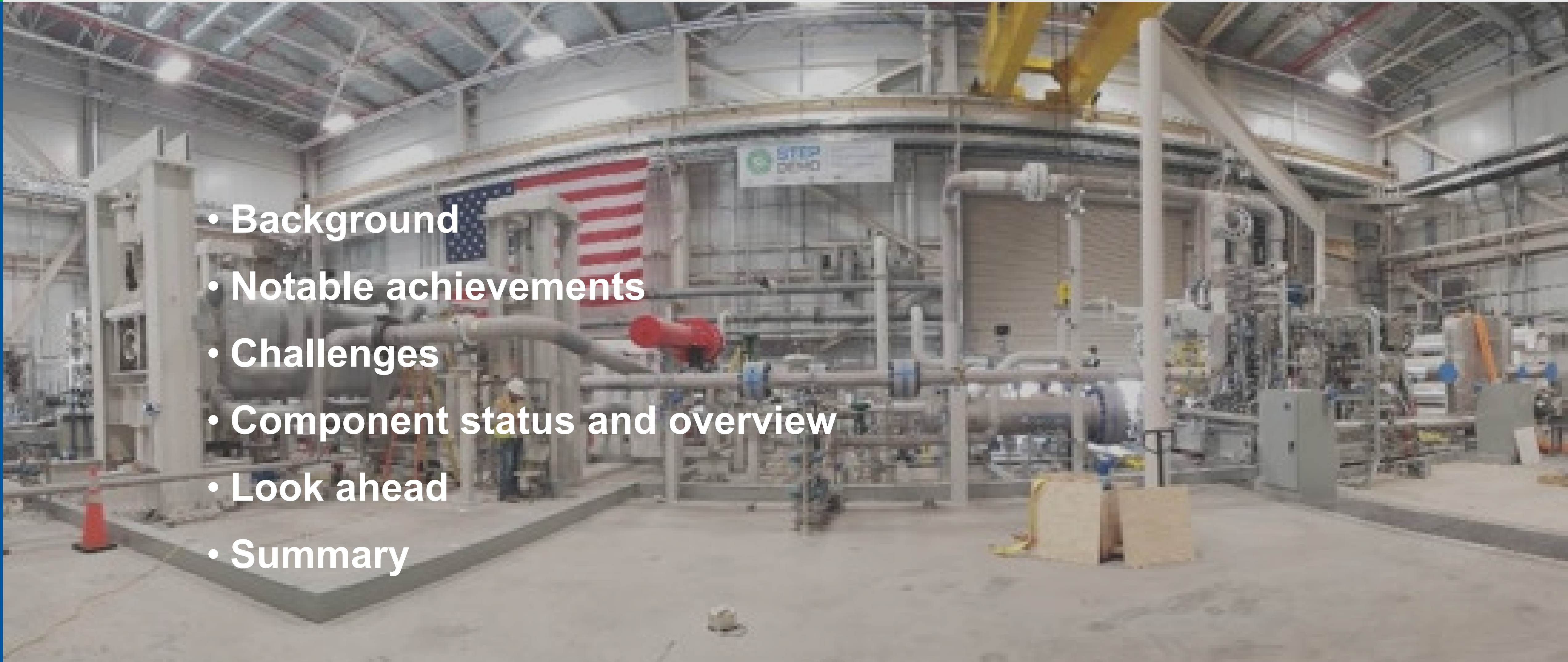
Agenda



- Background
- Notable achievements
- Challenges
- Component status and overview
- Look ahead
- Summary

Why is it Important? sCO_2 Power Cycles Offer:

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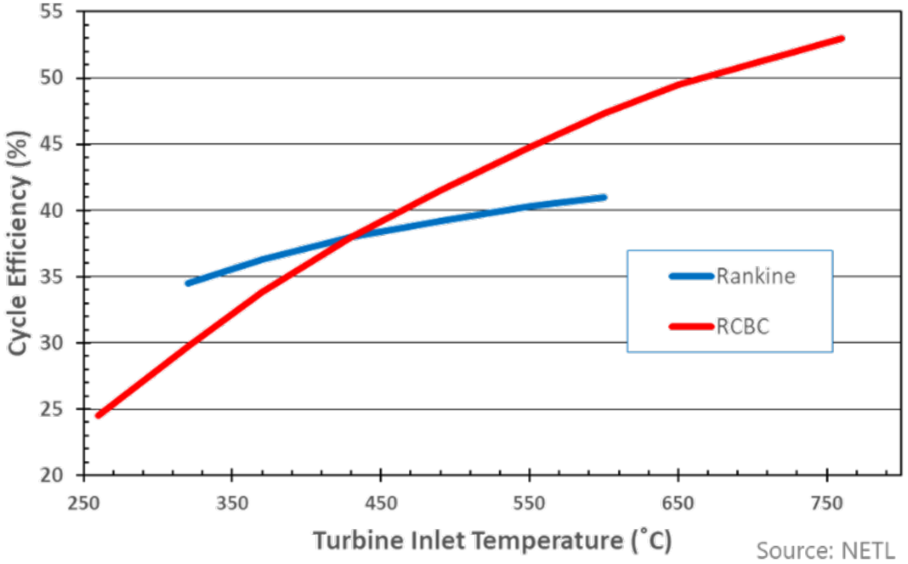
Efficient, Compact, Scalable, low water, low-carbon power generation

- 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

Greater cycle efficiency than steam Rankine cycle at high turbine inlet temperatures



Source: NETL

Improve power plant efficiency

Reduce costs, emissions, water use

Compact: small size turbomachinery

Quick response time

Zero emissions configurations

Versatile technology with many applications

Versatile Technology – Broad Applicability

Concentrated Solar

Fossil Fuel/Biomass

Geothermal

Nuclear

Energy Storage

Waste Heat Recovery

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Supercritical Transformational Electric Power (STEP) Demo Project

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- $165.6M 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:**

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- **Industry Co-Funders:**

KEPCO KOREA ELECTRIC POWER CORPORATION | Natural Resources Canada / Ressources naturelles Canada | Southern Company | Texas Commission on Environmental Quality | ENGIE | CSIRO | AMERICAN ELECTRIC POWER BOUNDLESS ENERGY | EGAT Power for Thai Happiness

www.STEPdemo.us

Project Objectives

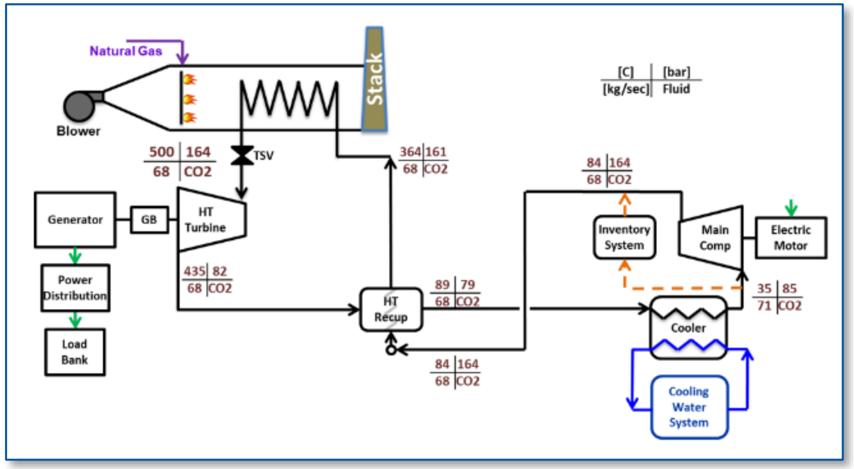
Simple Cycle Objectives

- Demonstrate initial cycle performance with reduced risk configuration
- Turbine inlet near **500C** similar to waste heat recovery applications
- Provide steady and transient cycle performance data used to predict RCBC performance and operation

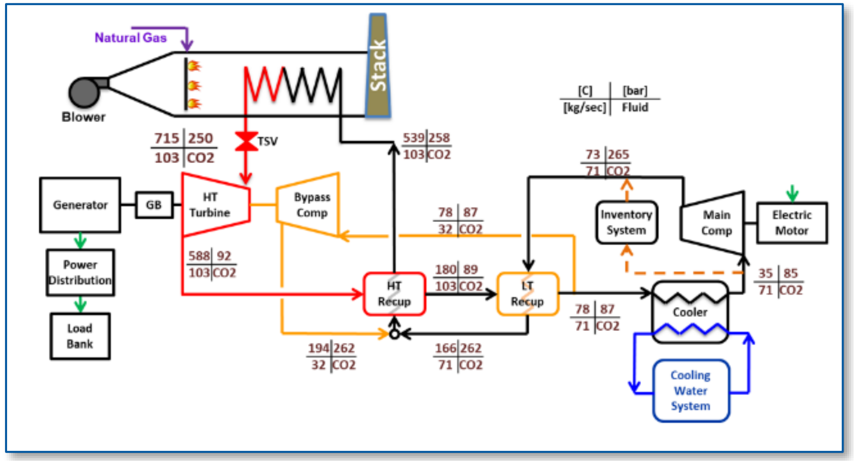
RCBC Objectives

- Demonstrate high performance cycle with parallel compressors and multiple heat exchangers
- Increase turbine inlet temperature to **715C**
- Measure steady and transient cycle performance data, evaluate operability
- Demonstrate pathway to 50% thermal efficiency

Current Budget Period: Simple Cycle



Next Budget Period: RCBC configuration



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Timeline to Test Operations

We are here

2016 - Oct
Project Start

2018 - Oct
Groundbreaking

2019 - Jan
Facility design complete

2020 - May
Building Completed

2023 - Oct
Mechanical Completion

2024 - Mar
Simple Cycle Testing to be completed

2025
RCBC Testing to be completed

Notable Achievements

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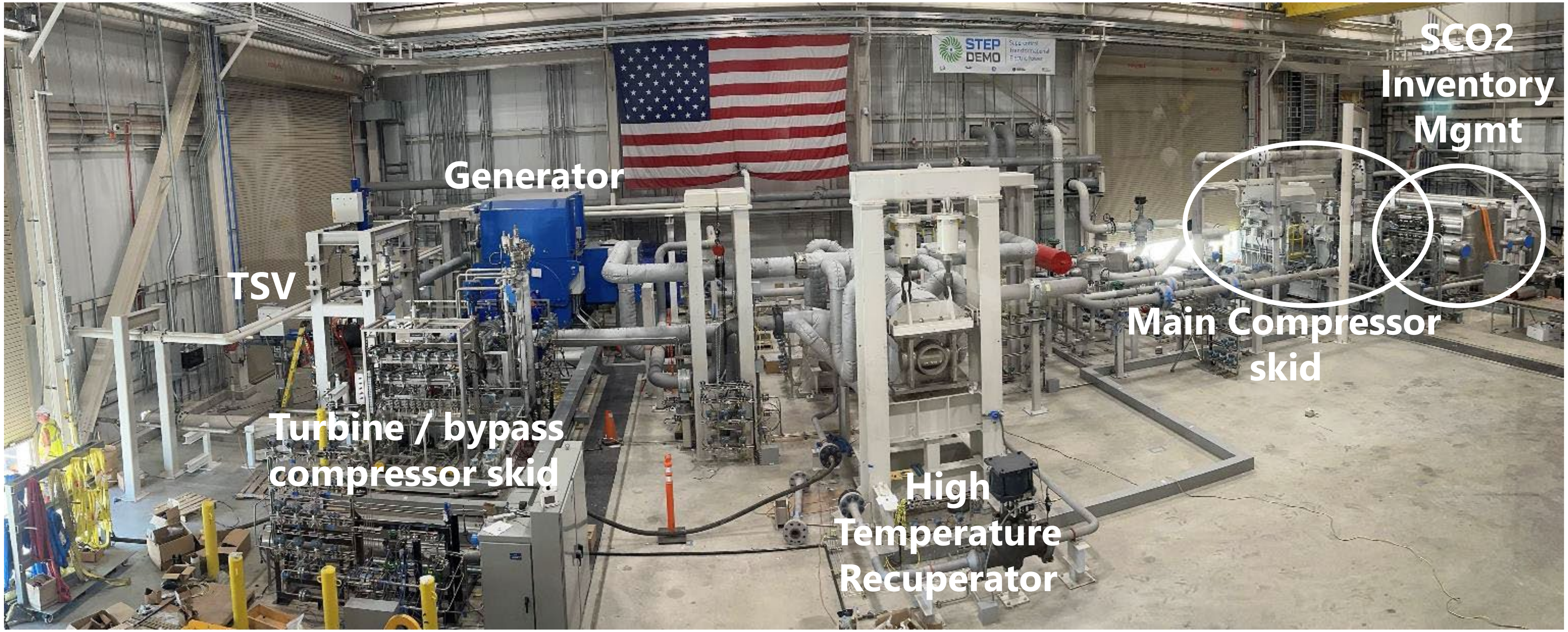
- Built the world's largest indirect-fired sCO2 power plant at 10 MWe
- Achieved Mechanical Completion for the Simple Cycle Configuration
- Successfully demonstrated full loop operation



More Notable Achievements

High temperature recuperator (HTR)

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

sCO2 turbine

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

Heater

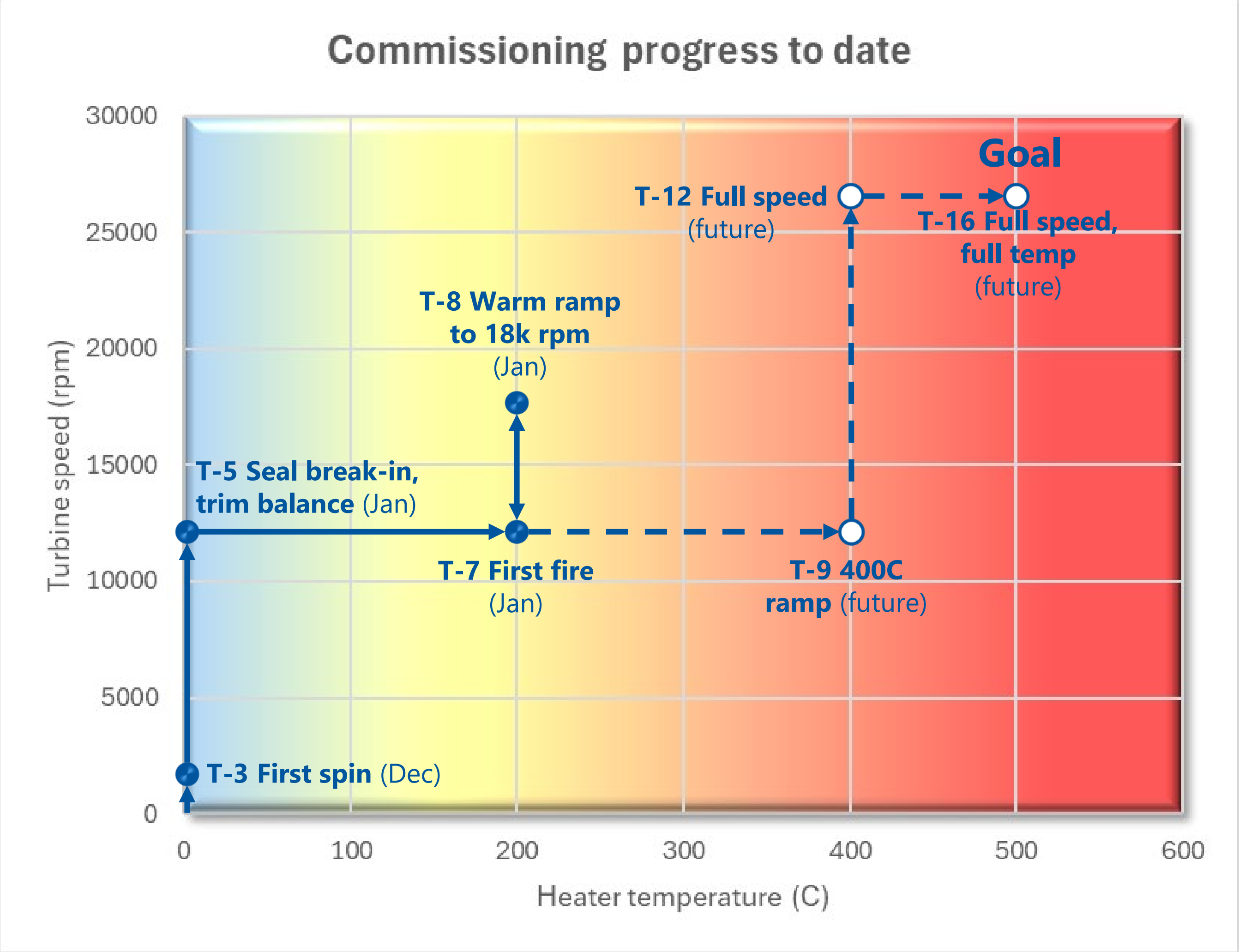
- World's largest high temperature Inconel heater tube bundle
- 22.54 MWth tube bundle heat duty

Turbine stop valve

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

STEP Commissioning progress to date

- Started system level tests in December 2023 with the turbine first spin
- First hot fire tests in January
- Achieved turbine speed of 18,000 rpm and heater outlet / turbine inlet temperature of ~200C
- Goal is to get to turbine speed of 26,600 rpm and turbine inlet temperature of 500C
- Performance testing to follow



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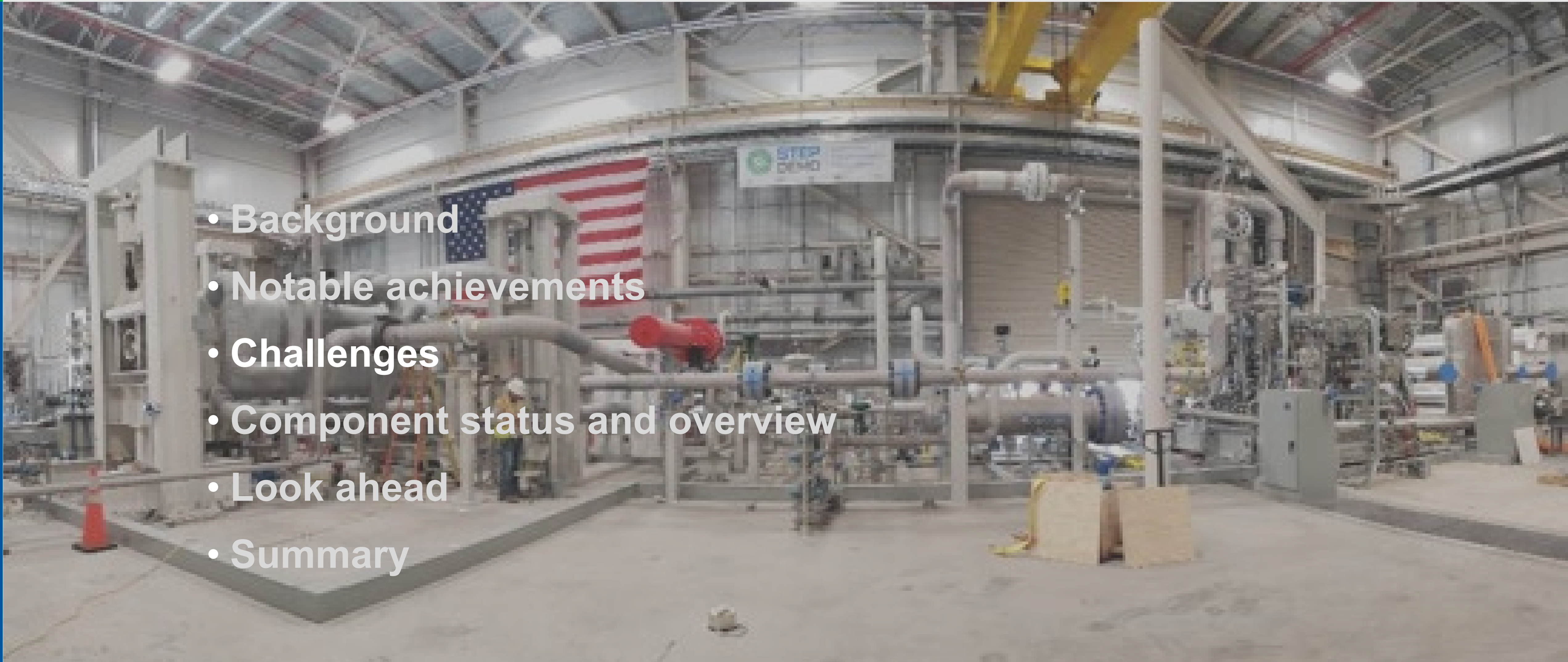

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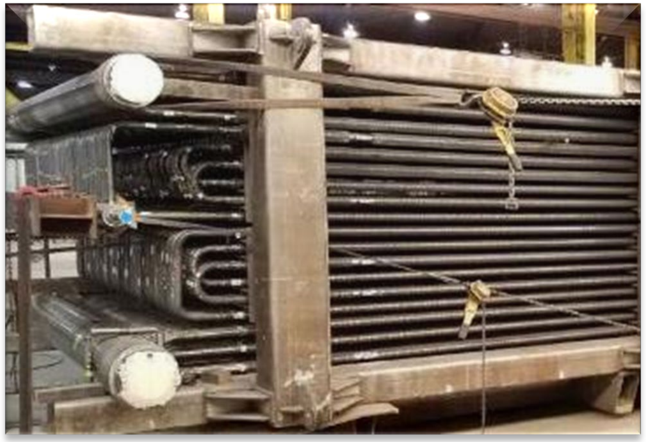
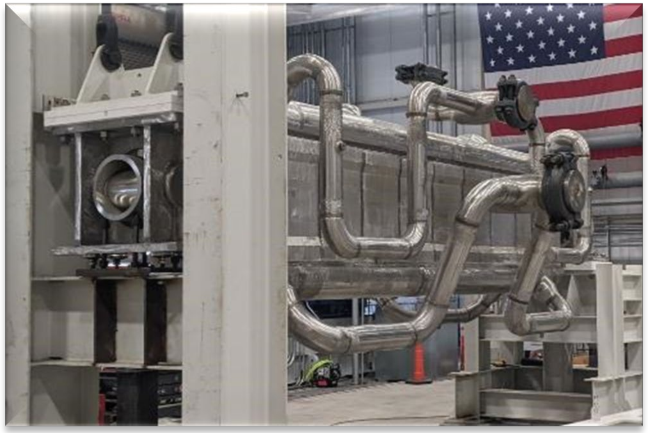
Challenges

- **Fabrication of high temperature components**
  - **Heater 740H tube bundle** – 3% of tube-to-tube butt welds failed inspection
    - Cause: Stress relaxation cracking during post-weld heat treat
    - Resulted in improved weld and inspection techniques including 100% phased array ultrasonic testing
  - **High temperature turbine stop valve** - New casting method developed
    - 3 simultaneous pours to cast Haynes 282 to minimize O_2 entrainment that cause inclusions in the metal
  - **High temperature recuperator** – Significant design challenge at scale
    - Temperature differential between the hot and cold side of the recuperator causes bending



Heater tube bundle



High temperature recuperator

More Challenges

- Developing components at small scales – challenges with turbine shaft dynamic loads
  - One benefit of sCO2 is its high density (similar to liquid water) that enables smaller equipment
  - Results in turbomachinery with relatively large masses at each end and with the relatively small diameter of the turbine shaft in the middle
    - Torsional dynamic loads in the case of a generator short circuit were difficult to manage at the 10 MWe scale
  - Led to decision to move main compressor to a separate skid

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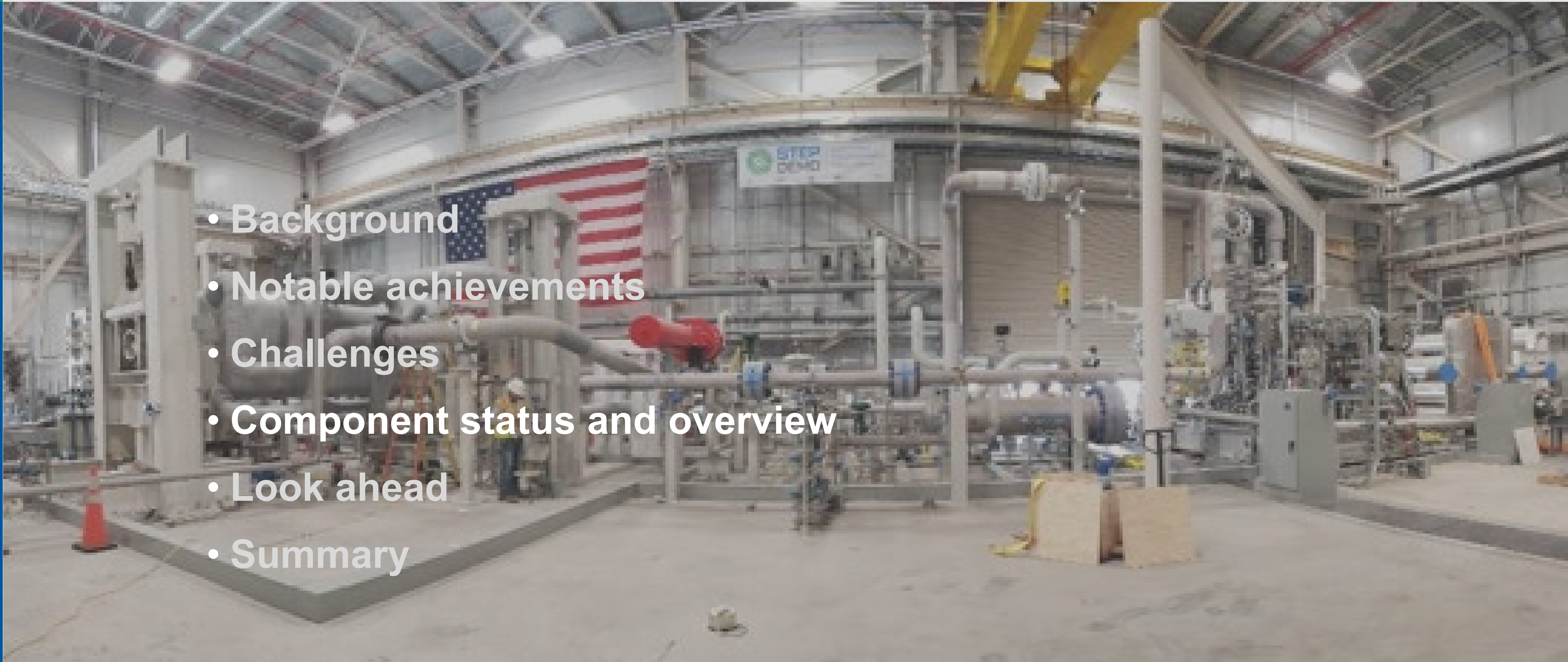

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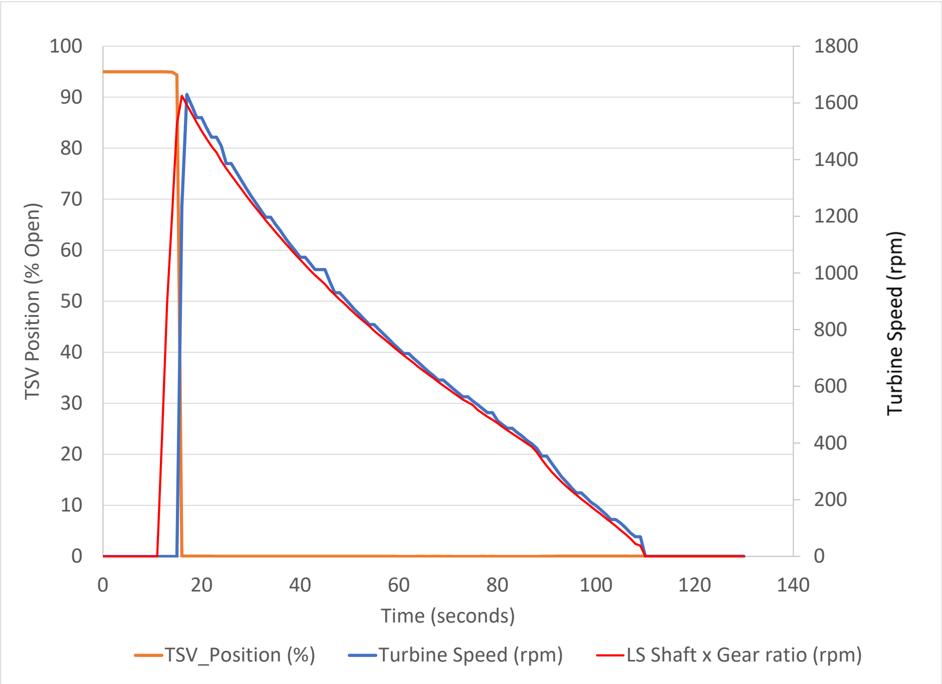
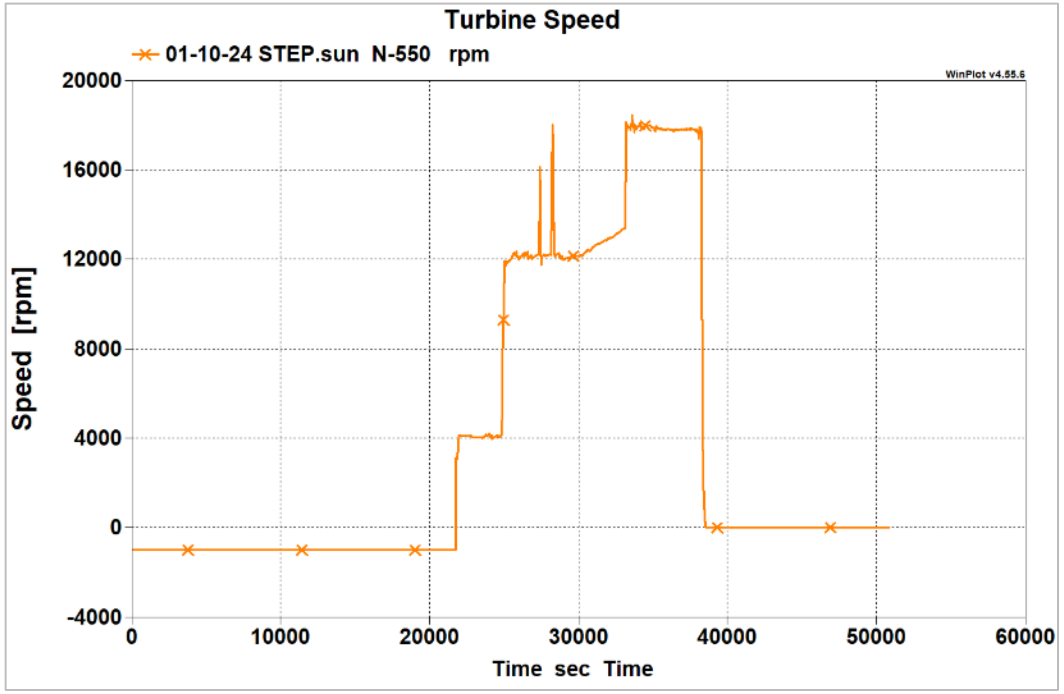
Turbine

- **Status**
  - Currently undergoing system level commissioning
  - Achieved TiT of 200C, with design temperature of 715C
- **Lessons Learned**
  - Thermal management is key to **dry gas seal life** (from Sunshot)
    - Delivery of warm seal gas is required at all times when the system is pressurized near the critical pressure (>50 bar)
  - The turbine case was designed with **vibrational modes** in the operating speed range
    - Designed to keep modes at low speeds to minimize excitation
    - Validated by modal testing
    - Vibration showed low response through the speed range
  - Axial turbine design **scalable** to 100+ MW

Turbine



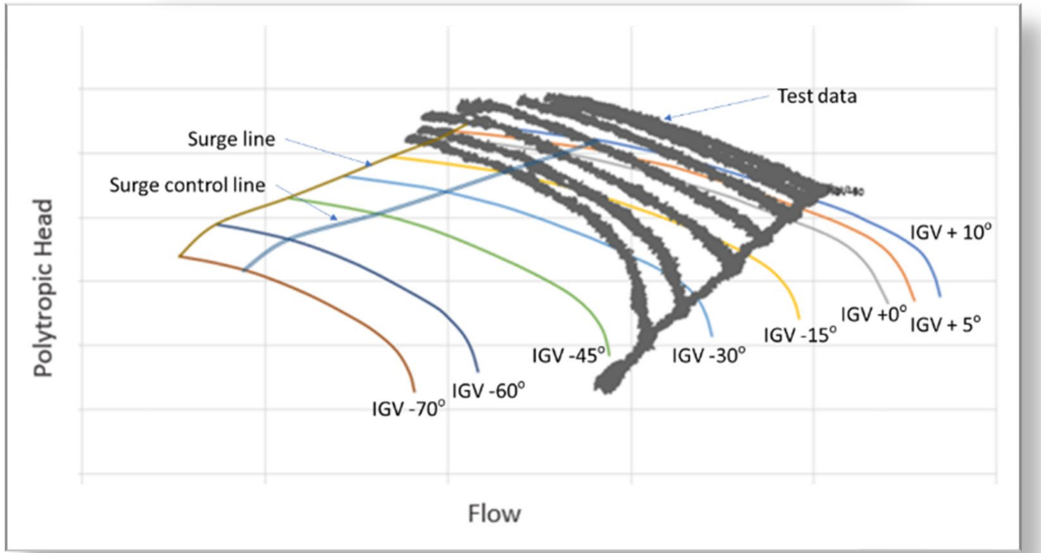


- **First spin:** Ramped up to 1600 rpm in December 2023
  - Overspeed trip set to 1000 rpm to ensure speed remains low

- **Max speed to date:** Achieved 18,000 rpm in January
  - Short bumps to 16k and 18k rpm prior to check vibration levels prior to extended run

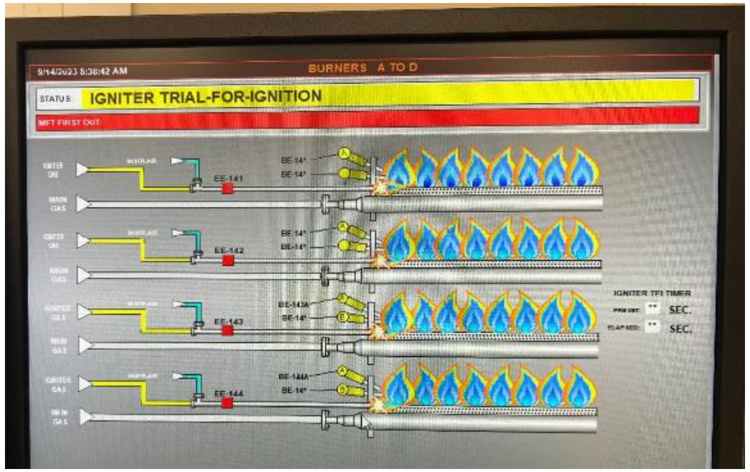
Compressor

- **Status**
  - The compressor loop was successfully commissioned (including the cooling tower, sCO2 inventory management system and main process cooler)
  - Compressor skid is now supporting system commissioning
- **Lessons Learned**
  - Actual compressor maps were significantly **different than predicted**, resulting in 2X reduction in turndown capability
  - Accurate compressor efficiency is difficult to measure at 21k rpm with existing instrumentation. This is why a **torque meter** was installed.
  - **Liquid operation** (at low speed) is important capability for system startup



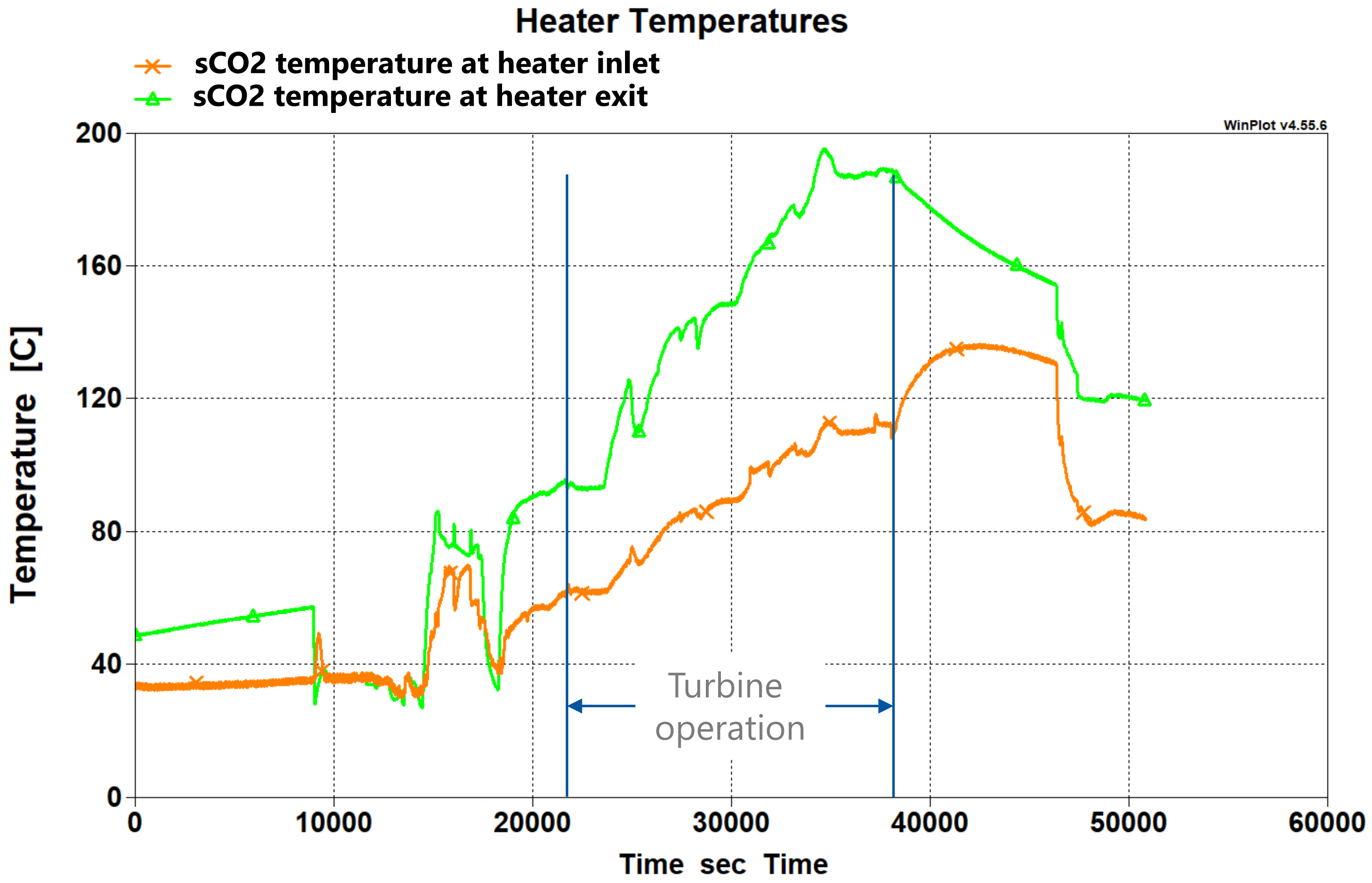
Heater

- **Status**
  - Heater is mechanically complete and supporting system commissioning
  - Gas path burnout was completed with multiple light-offs and 4 hours of continuous operation
  - Selective Catalyst Reduction emissions control system **ready for** commissioning during **full fire** operation
- **Lessons Learned**
  - How to better **weld 740H** material and minimize weld cracks after post-weld heat treat
    - Use of **phased array ultrasonic** testing to inspect all tubes
    - Fabrication/NDE knowledge is transferrable to commercial applications
  - Used **air cooling** instead of CO2 for heater burnout to accelerate schedule, but also provided safer work environment (no CO2)



Heater

- Heater operation during a system commissioning test in January 2024
  - Delivered sCO2 approaching 200C during turbine operation
- Future commissioning tests will ramp the temperature up to 500C



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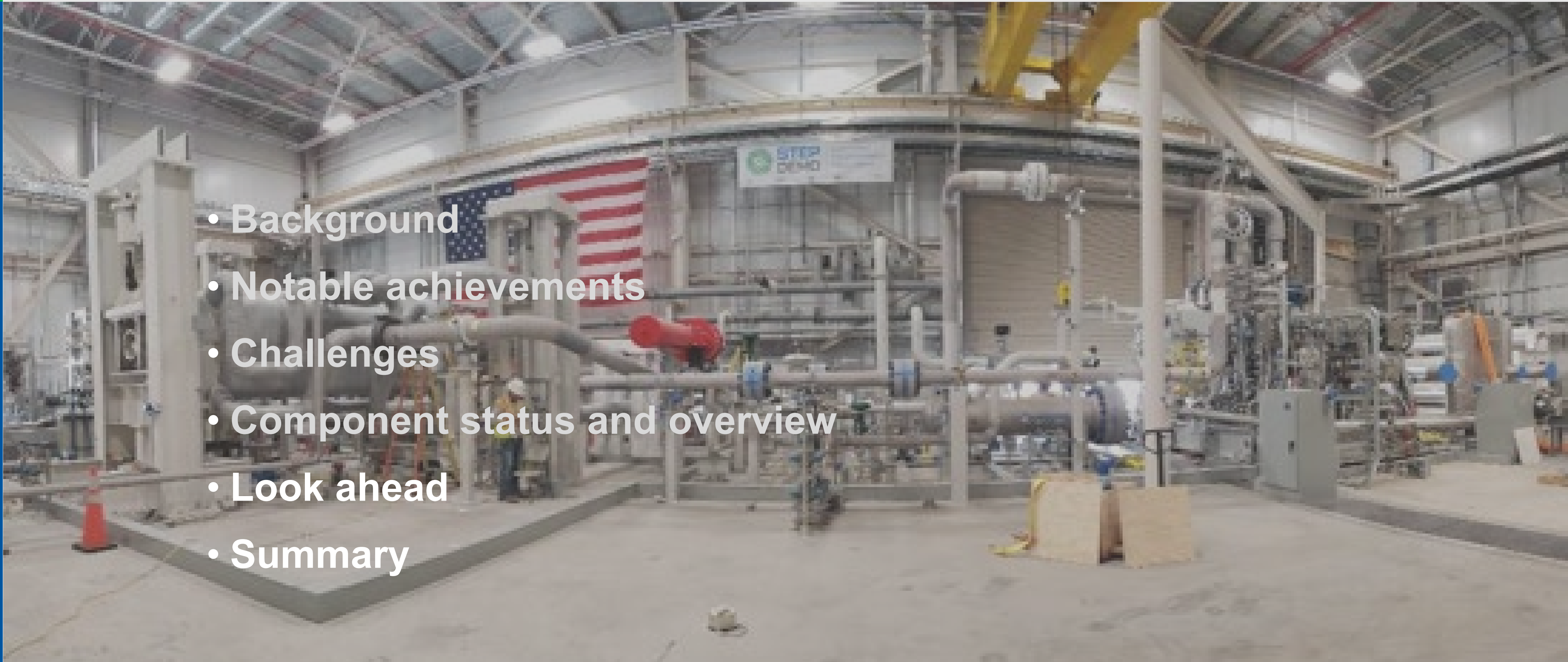

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Timeline to Test Operations

- **Aug 2023** – Compressor Acceptance Testing
- **Oct 2023** – Mechanical Completion – Simple Cycle
- **Apr 2024** – Complete Commissioning Simple Cycle
- **May 2024** – Complete Simple Cycle Tests
- **Apr 2025** – Complete RCBC Reconfiguration
- **Feb 2026** – Complete RCBC Tests (End Project)

Summary

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- **The STEP project pushes the envelope for an indirect-fired sCO2 plant**
  - World' largest: plant, high temp Haynes 282 casting (TSV), high temp PCHE (HTR), and high temp Inconel heater tube bundle (heater), 740H piping installation
  - Highest power density terrestrial turbine
- **There are numerous lessons learned that are relevant to commercial applications**
  - Fabrication experience with high temperature materials was advanced for PCHE (HTR), Haynes 282 castings (TSV) and Inconel 740H applications (heater, turbine casing, piping)
  - Thermal management is key to turbine dry gas seal life, even during pressurized holds
  - Turbine designed to be scalable to 100+ MW
  - Identified gaps in knowledge and performance for commercial sCO2 compressors
  - Liquid operation is an important compressor requirement for cold start-ups
  - Commissioning the heater with air instead of CO_2 accelerates schedule and simplifies commissioning processes and safety precautions

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

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