sCO2, Ammonia and Hydrogen – Advanced Turbine System Technologies at GTI Energy

W. Follett
Program Director – SCO2 Technologies

UTSR Keynote
11/2/2023

Agenda

GTI ENERGY

- Introduction
- Membrane reactor
- Ammonia combustion
- Supercritical CO_2 – STEP power plant status
- Summary

Carbon Management & Conversion Technology Areas

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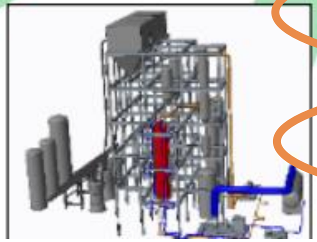
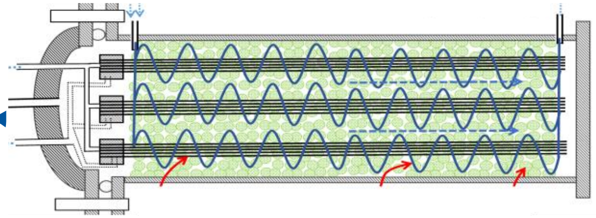


- Subsurface Technologies
- Bio-Energy
- Combustion
- Gasification
- Hydrogen
- Oxy-Combustion
- CO_2 Capture & Separations
- Power Conversion (sCO_2)

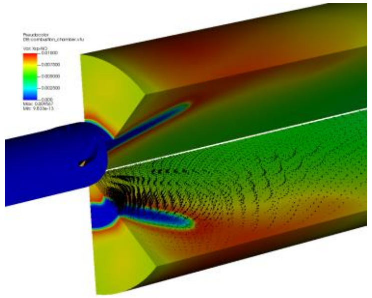



Advanced Turbine System Technologies

- Developing 3 technologies focused on clean energy production
  - Clean ammonia and hydrogen production and transport
    - Clean ammonia as H_2 carrier for efficient transport and storage
    - Membrane reactor technology development for high purity H_2 separation
  - Turbine combustor technology that utilizes ammonia as a zero-carbon fuel
  - Supercritical CO2 (sCO2) power generation effectively utilizes low- or zero-emissions heat sources
    - Concentrated solar, nuclear, fossil/bio with carbon capture, waste heat, energy storage



Membrane reactor



Ammonia combustor

sCO2 power generation

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Hollow fiber membrane reactor: High purity H_2 from green ammonia

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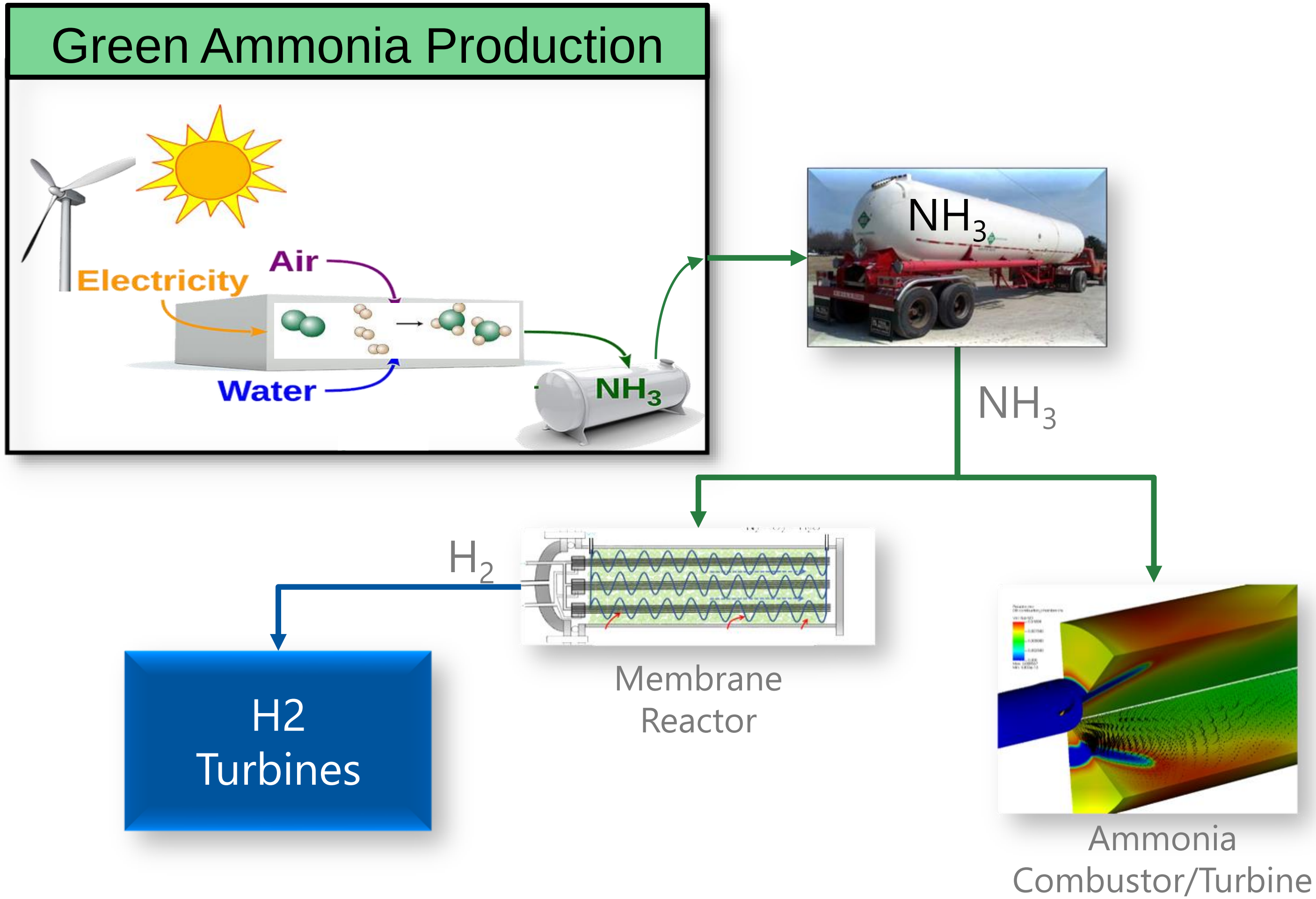
NH_3 storage and transport

- 2,750 kg equivalent H_2 on truck
- 620 kg equivalent H_2 in nurse tank
- 18 bar operation pressure
- 1 station fill per **WEEK**

Gaseous H_2 storage and transport

- 350 kg H_2 (entire truck)
- 160 bar operation pressure
- >1 station swap tube trailer per **DAY**



Vision of ammonia as a hydrogen carrier for ease of transport and storage

Our technology: Hollow fiber membrane reactor at <450°C for high purity H_2 from NH_3 decomposition

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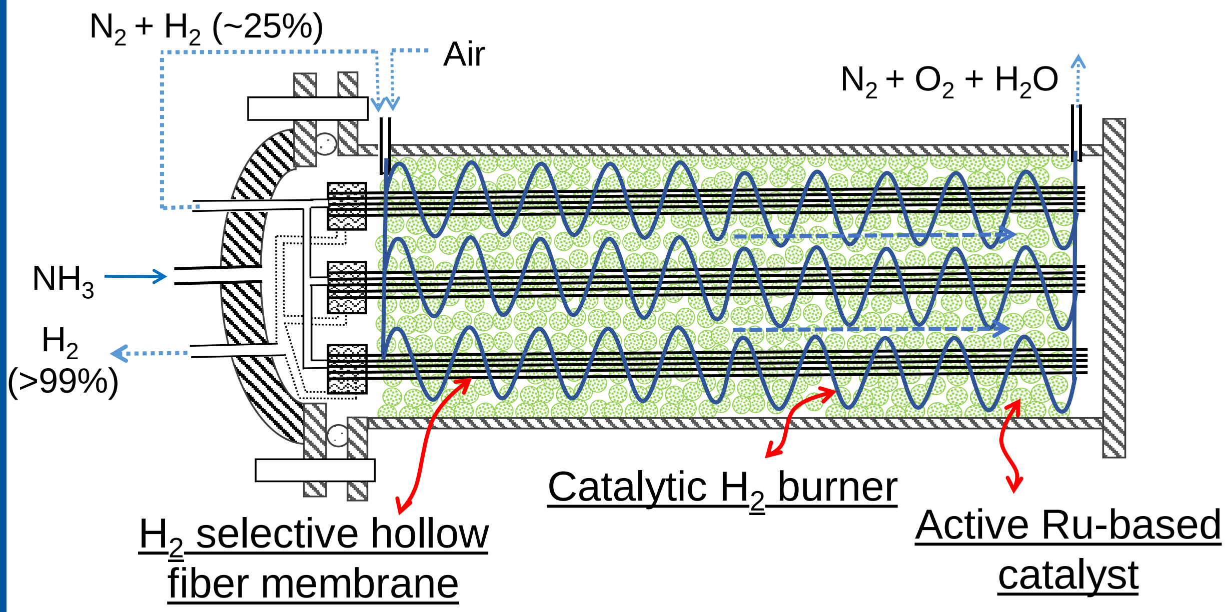
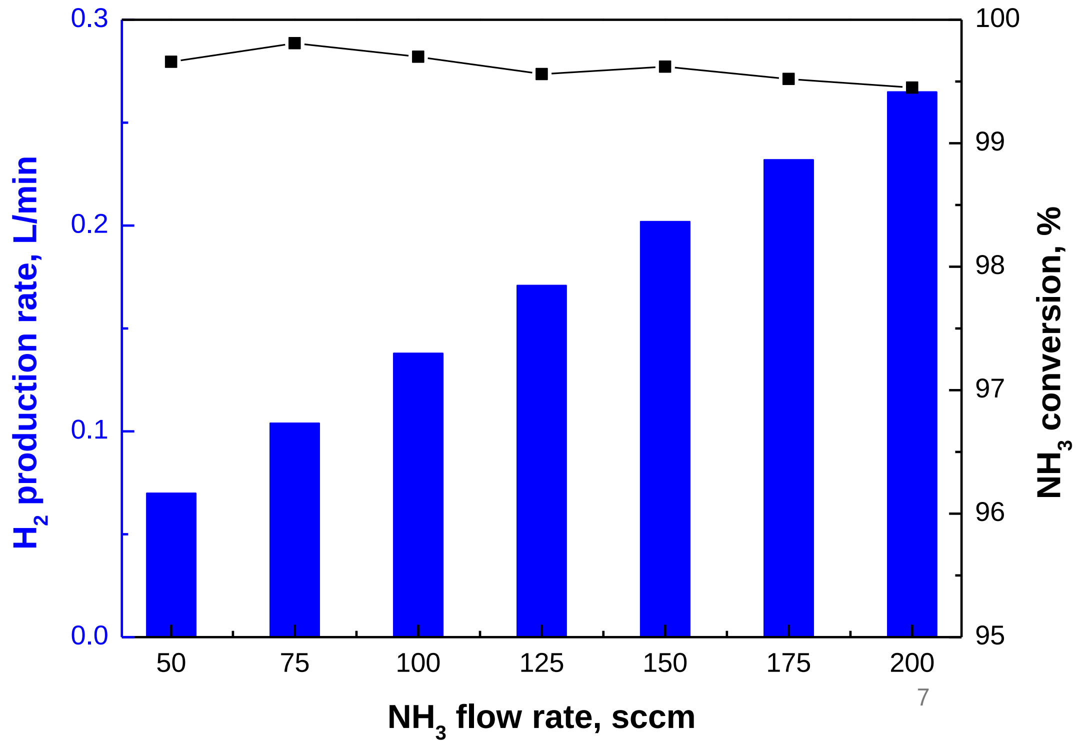
The Technology

- Novel, self-sustained membrane reactor design
- Highly active, lower cost, promoted Ru-based bimetallic catalyst enables high conversion at <450°C
- H_2 selective membrane separates NH_3 decomposition stream to generate high purity H_2

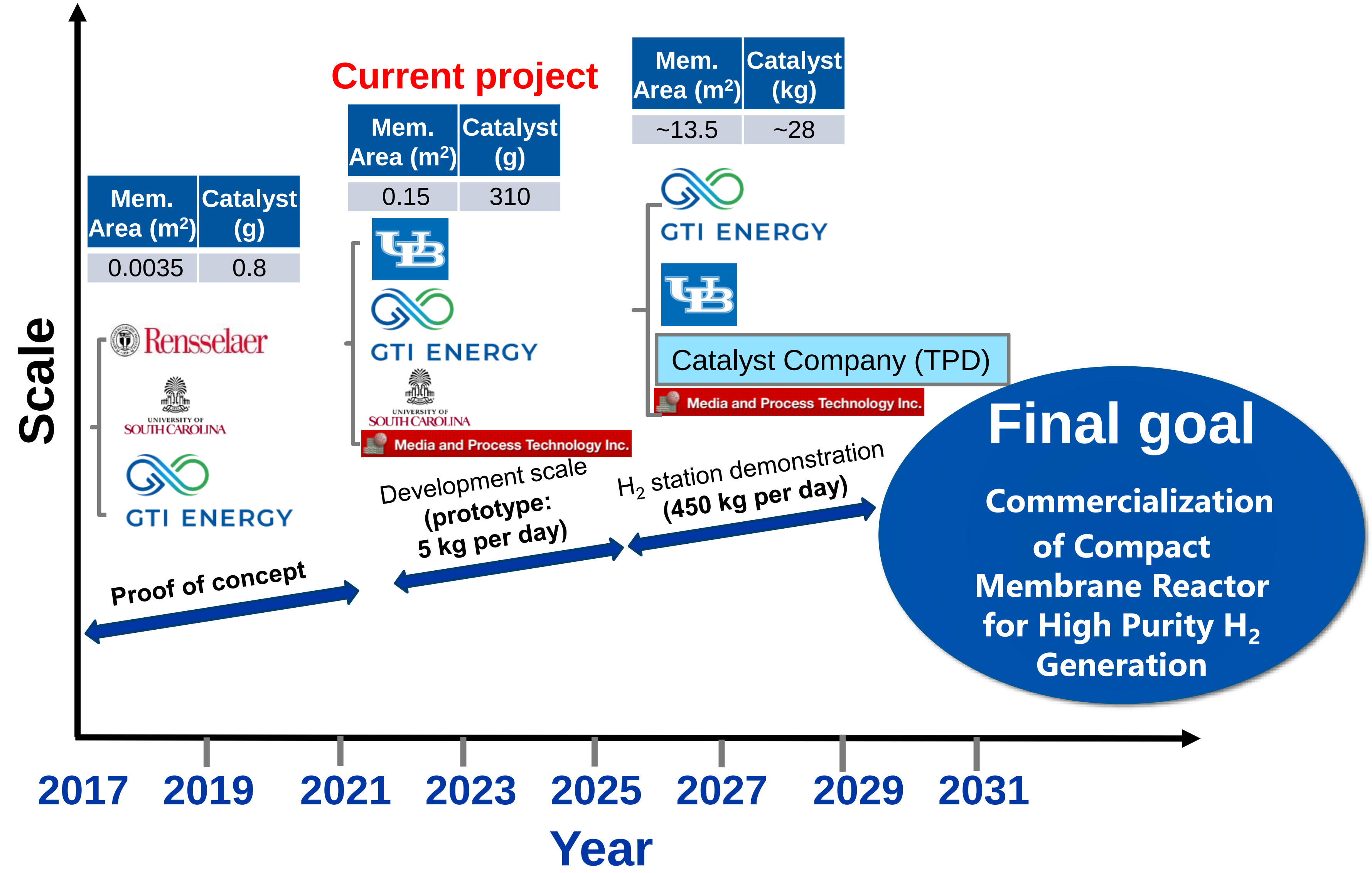


Representative Results

	Goal	Achieved
Energy efficiency	>80%	87%
H_2 high purity	>99%	>99.9%
NH_3 conversion	>99%	>99.5%
Product NH_3 concentration	<100 ppb	<10 ppb



Technology development path



Mem. Area (m^2)	Catalyst (g)
0.0035	0.8

Mem. Area (m^2)	Catalyst (g)
0.15	310

Mem. Area (m^2)	Catalyst (kg)
~13.5	~28

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Investigation of Ammonia for Combustion Turbines (IACT)

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- Goal - develop advanced combustor technology to utilize ammonia as a zero-carbon fuel for power generation applying an iterative physics, computational, and experimental approach resulting in a pilot combustor design validated through tests
- Ultimately testing Scaled Combustor
  - Design using updated mechanism/ validated model
  - NOX Target: 20 ppm at 15% O_2
  - High combustion efficiency
  - Stable flame (no blowoff)
- Challenges with ammonia
  - Safety considerations with ammonia
  - Ammonia ignition and flameholding
  - NOx generation

	Methane	Hydrogen	Ammonia
Lower Heating Value (LHV)	Mass: 50 MJ/kg (21,500 BTU/lb) Volume: 915 BTU/scf	Mass: 120 MJ/kg (51,600 BTU/lb) Volume: 275 BTU/scf	Mass: 18.6MJ/kg (8,000 BTU/lb) Volume: 365 BTU/scf
Flame Speed (S_L)	37 cm/s (1.2 ft/s)	291 cm/s (9.5 ft/s)	7 cm/s (0.23 ft/s)
Flame Temperature (T_{ad})	1950°C (3542°F)	2110°C (3830°F)	1800°C (3272°F)

Comparison of fuel characteristics

GTI ENERGY · EPRI ELECTRIC POWER RESEARCH INSTITUTE · UCF UNIVERSITY OF CENTRAL FLORIDA · Georgia Tech · CRAFT Tech · LCRI LOW-CARBON RESOURCES INITIATIVE

IACT Plan & Key Roles
Schedule: 9/2022-1/2026

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Understand SOA and identify knowledge gaps

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Led Literature Review & Design Def.

Fundamental NH_3 & NH_3+H_2 combustion physics testing

UCF UNIVERSITY OF CENTRAL FLORIDA

Shock Tube & Flame Speed Tests Kinetics mech.

&

Georgia Tech

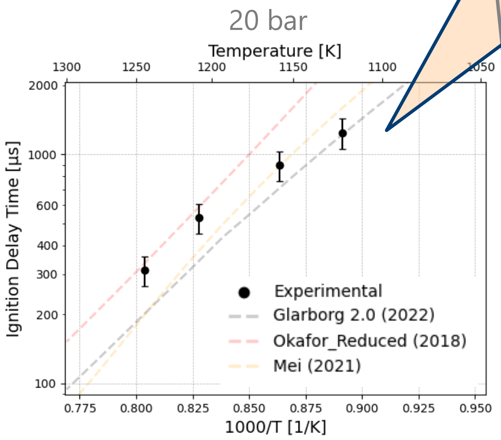
Hencken Burner & Fuel Staging Tests; Kinetics mech.; Analytical design

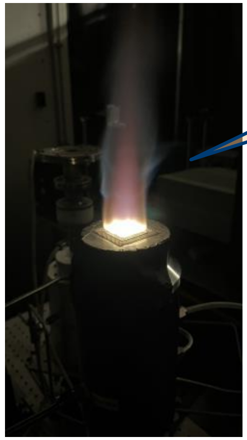
Develop CFD design tool implementing updated mechanisms

CRAFT Tech

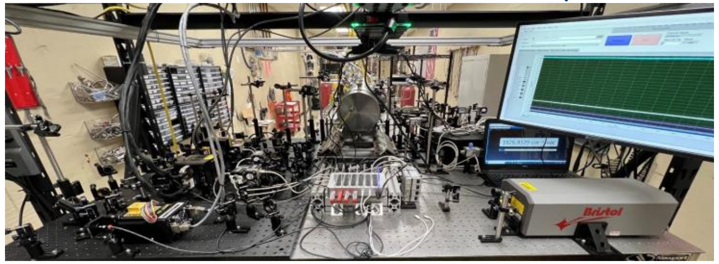
CFD Tool Devel.; Scaled Combustor Design

Models Need Improvement – Gathering Data





Ammonia flame

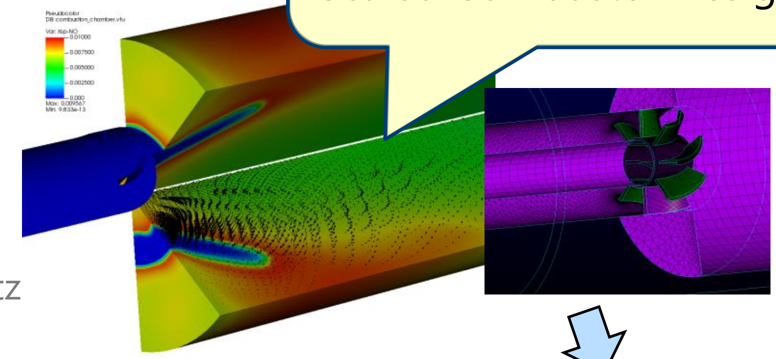


Shock Tube

Quartz Tube

Burner

Main Fuel-Air



Design and test scaled combustor

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Reqt's Def. & Scaled Comb. Design, Fab. & Test

Georgia Tech

Scaled Comb. Test

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Supercritical Transformational Electric Power (STEP) Project

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Scope: Design, construct, commission, and operate a **10 MWe sCO_2 Pilot Plant Test Facility** - reconfigurable to accommodate other testing

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

<u>Joint Industrial Partners</u>:

KEPCO Korea Electric Power Corporation · Natural Resources Canada / Ressources naturelles Canada · Southern Company · American Electric Power · ENGIE · CSIRO · Texas Commission on Environmental Quality · EGAT Power for Thai Happiness

Schedule: Three budget phases (2016-2025)

Cost: $165.6MM Total / $124.5MM Federal Funding (includes building)

STEP DEMO
www.STEPdemo.us

U.S. Department of Energy · National Energy Technology Laboratory · GTI Energy · SwRI · GE

Why is it Important? sCO_2 Power Cycles Offer:

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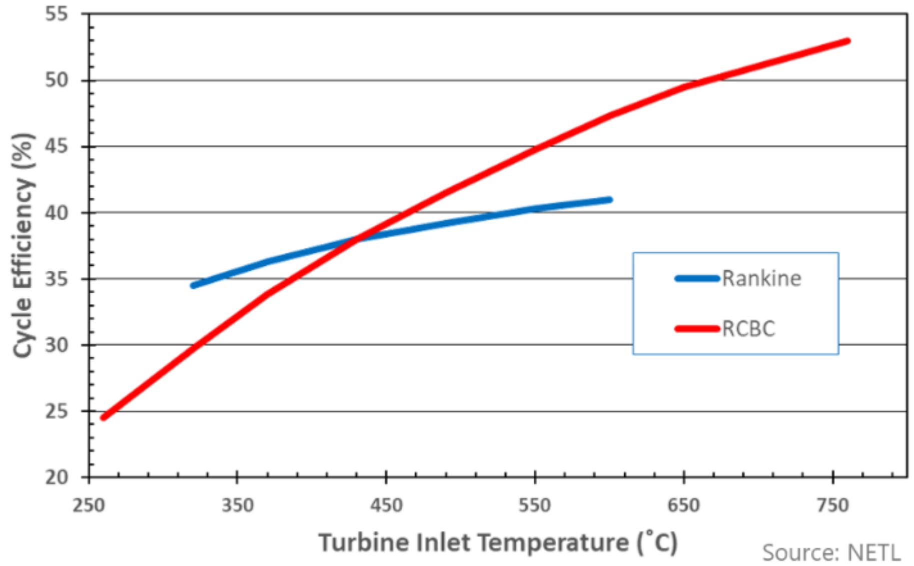
Efficient, Compact, Scalable, low water, low-carbon power generation

- 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

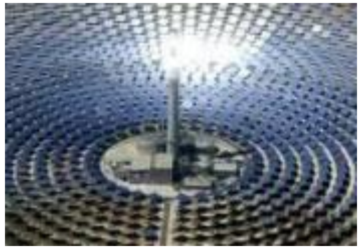
Compact: small size turbomachinery

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

Timeline to Test Operations

You are here

2016- Oct
Project Start

2018 - Oct
Groundbreaking

2019 - Jan
Facility design complete

2020 - May
Building Completed

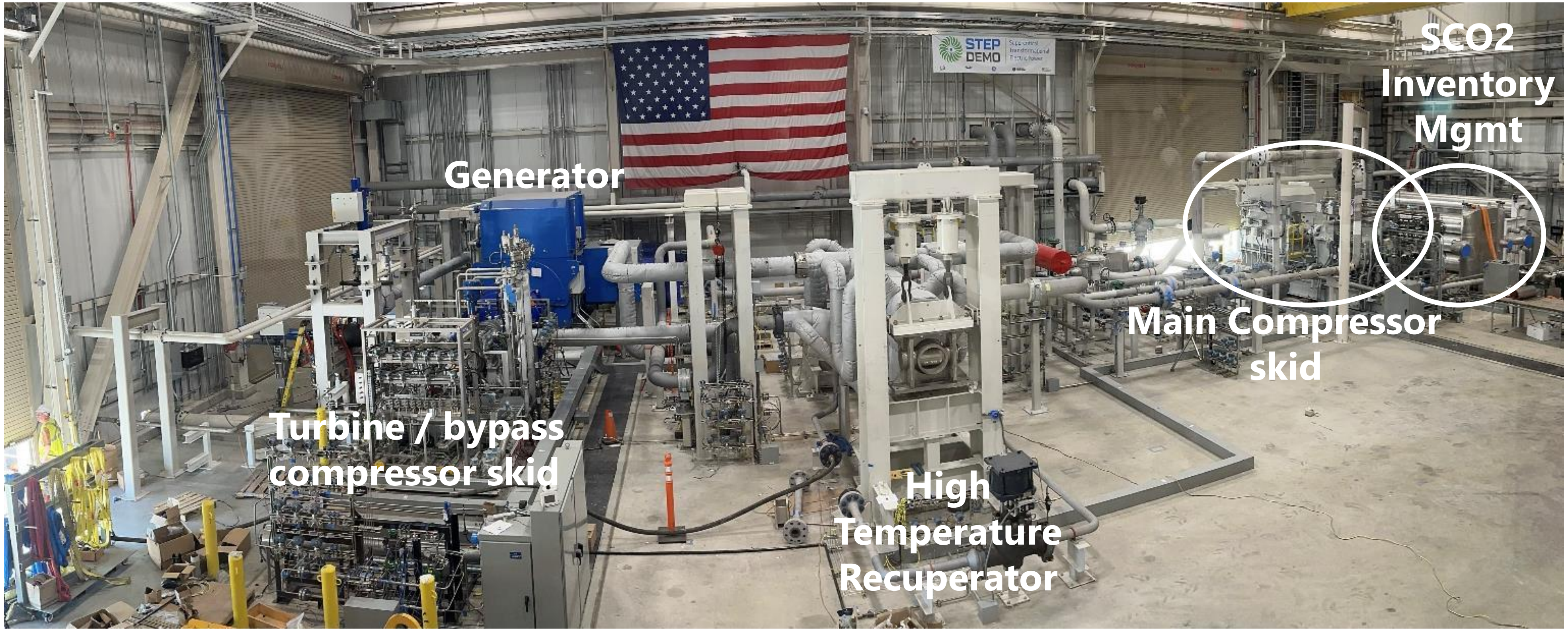
2023 - Oct
Mechanical Completion

2024 - Feb
Simple Cycle Testing to be completed

2025
RCBC Testing to be completed

Notable Achievements

- Built the world's largest indirect-fired sCO2 power plant at 10 MWe
- Achieved Mechanical Completion for the Simple Cycle Configuration
- Successfully demonstrated the compressor loop (Cooling tower, compressor, main process cooler, Inventory Management System)



Mechanical Completion Ribbon Cutting

October 26, 2023


STEP
DEMO

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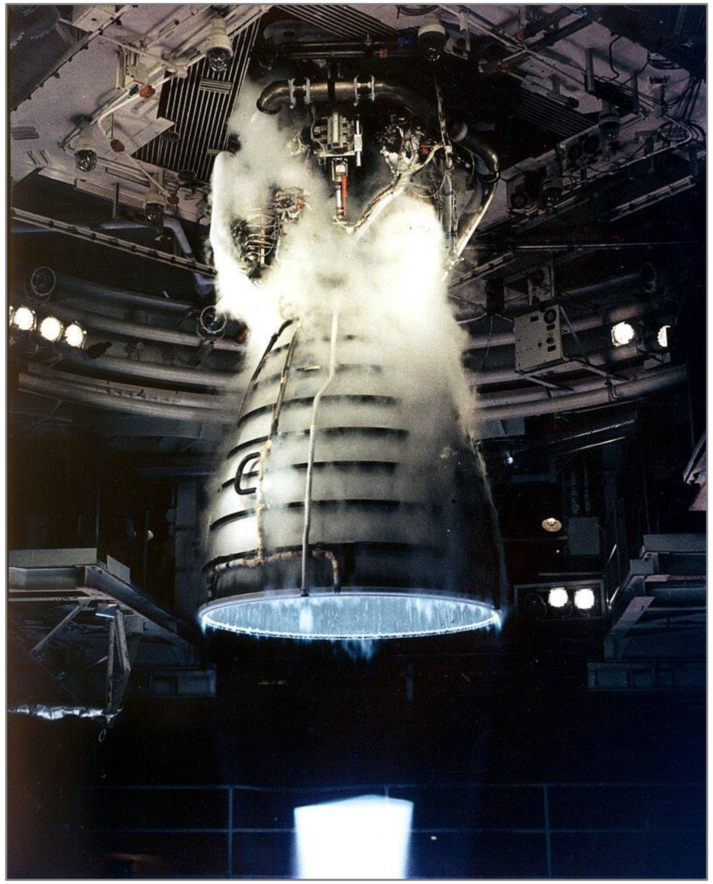

?

Is STEP rocket science?

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Category	HPOTP (Rocket)	STEP	Verdict
Speed	28,000		
Power	23,260 hp		
Size	24 x 35 inches		
Weight	Not found		
Lifespan	Hours		

HPOTP = High pressure oxidizer turbopump

ChatGTP: STEP is NOT rocket science

More Notable Achievements

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sCO2 turbine

- At ~1/10 the size of an equivalent steam turbine, has the world's highest power density for a terrestrial turbine
- 21,500 horsepower produced by 180 lb rotor (120 HP/lb, or 200 kW/kg)

High temperature recuperator (HTR)

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

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 Turbine

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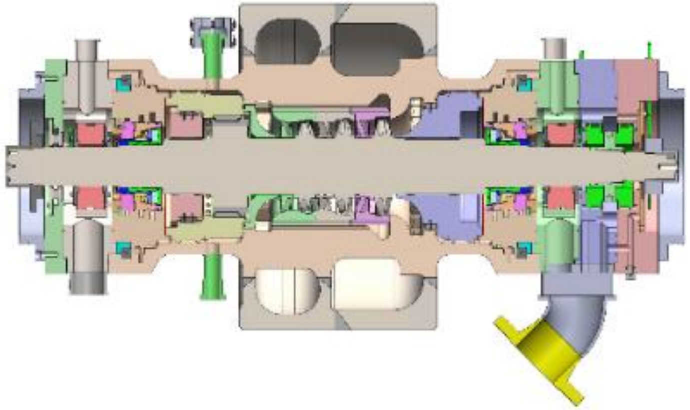
STEP Demo Turbine

- Objective: Advance Turbine from TRL 6 (Engineering Prototype) to TRL 7 (Full Scale Prototype)
- 16 MW gross power, 3 stages
- Fabricated barrel style casing
- Highest terrestrial power density at 200 kW/kg (120 hp/lb)



Lessons Learned

- Thermal management key to health of dry gas seals
  - Delivery of warm seal gas required at all times while pressurized
- Single piece rotor/blades required due to high power but had long lead time.
  - Individual blades possible at larger scales.
  - Will seek alternate vendors to reduce lead time.
- Casing modes are in operating speed range. Placed at low speeds to minimize excitation.

Compressor

- **Status**
  – Compressor is mechanically complete
  – The compressor loop was successfully commissioned (including the cooling tower, sCO2 inventory management system and main process cooler)
  – Compressor was run at Simple Cycle and RCBC speeds
- **Lessons Learned**
  – Identified gaps in knowledge and performance for commercial sCO2 compressors
    - Compressor map performance was significantly different than predicted, resulting in reduction in turndown capability
  – Liquid operation is an important compressor requirement to support cold start capability
  – Compressor efficiency is challenging to calculate accurately at some conditions due to low delta T across the compressor. Installed torque meter and density meter to improve accuracy.

Summary

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- GTI Energy is pursuing a vision of ammonia as a hydrogen carrier due to ease of transport and storage
  - The membrane reactor supports this vision by providing high purity H_2 for use in hydrogen turbine applications
  - Development of ammonia combustor that can make use of ammonia directly for turbine applications
- STEP is the largest indirect-fired sCO2 facility in the world, and just achieved mechanical completion
  - It has significantly advanced high temperature material manufacturing capabilities
    - 740H heater tubes and piping
    - Haynes 282 for turbine stop valve
    - Largest high temperature PCHE using stainless steel
  - World's highest power density turbine at 120 hp/lb

STEP is BETTER than rocket science

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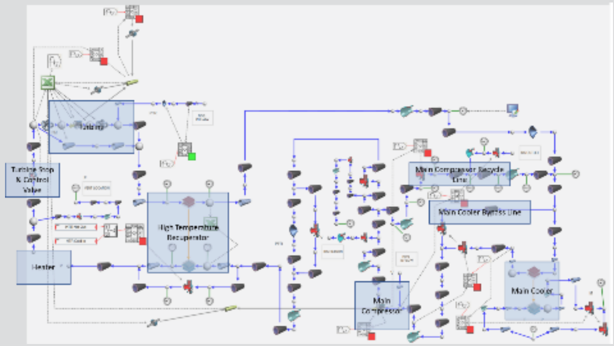
solutions that transform

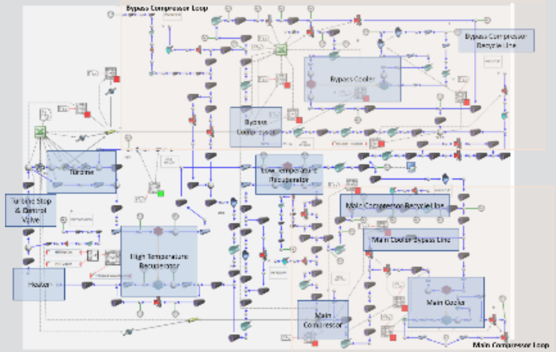
GTI Energy develops innovative solutions that transform lives, economies, and the environment

www.gti.energy

Steady State Modeling Summary



Simple Cycle Modeling



RCBC Cycle Modeling

Model Names	Cycle Configuration	Description	Load %	Net Power Level	Cooler Exit Temperature	Turbine Inlet Temperature	Cycle Efficiency
233	Simple	Simple cycle minimum load case MC 21k RPM (2022)	Min	1.8 MWe	35 °C	500 °C	17.56%
236	Simple	Simple cycle maximum load case MC 21k RPM (2022)	Max	4.6 MWe	35 °C	500 °C	26.67%
230	Simple	Simple cycle minimum load case MC 27k RPM (2020)	Min	3.0 MWe	35 °C	500 °C	18.14%
N/A	Simple	Simple cycle maximum load case MC 27k RPM (2020)	Max	8.9 MWe	35 °C	500 °C	30.81%
251	Recompression	Baseline case	100%	10.0 MWe	35 °C	715 °C	43.21%
252	Recompression	"Hot" Day Case	70%	6.7 MWe	50 °C	690 °C	38.15%
254	Recompression	Partial load case using inventory control	40%	4.0 MWe	35 °C	685 °C	37.86%
255	Recompression	RCBC at 500°C turbine inlet temperature	75%	7.5 MWe	35 °C	500 °C	33.51%
257	Recompression	Partial load case using TSV throttling (transient condition)	40%	4.0 MWe	35 °C	715 °C	35.59%
257a	Recompression	Partial load case using TSV throttling	40%	4.0 MWe	35 °C	682 °C	35.18%

Cycle Results Table

- **Status**
  - Models are complete and being actively used
  - Components models are based on vendor datasheets and operational constraints
  - Ongoing work: Test data is being used to update and validate the models as it becomes available
- **Lessons learned**
  - System analysis of 2021 compressor maps led to shifting Simple Cycle operations from 27k rpm to 21k rpm to maintain system performance
  - 2023 test data is currently being used to evaluate impact of actual compressor performance on system performance
    - 27k rpm shows minor improvement in system performance at Simple Cycle conditions. Other operating points under investigation.

Dynamic Model Summary

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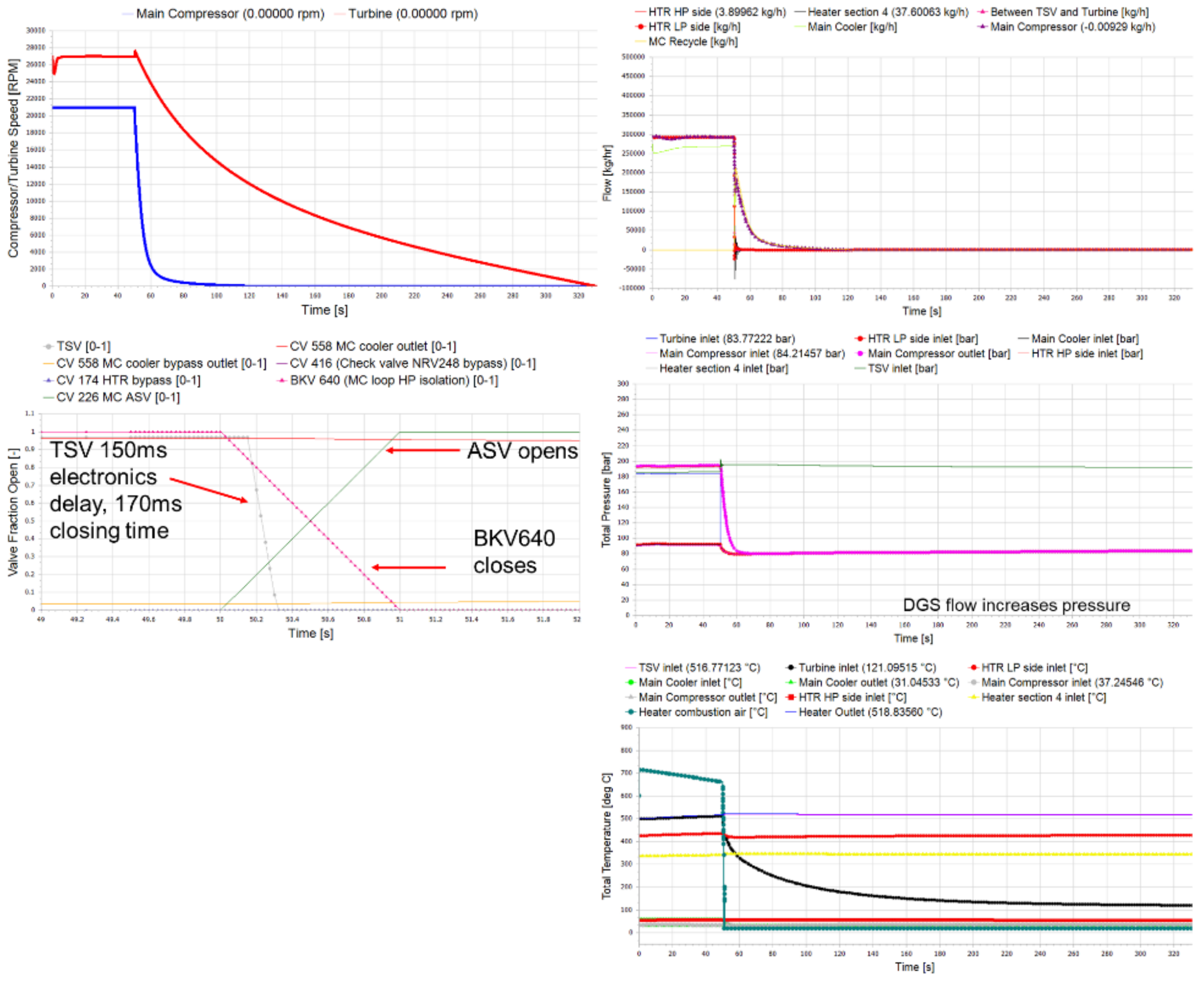
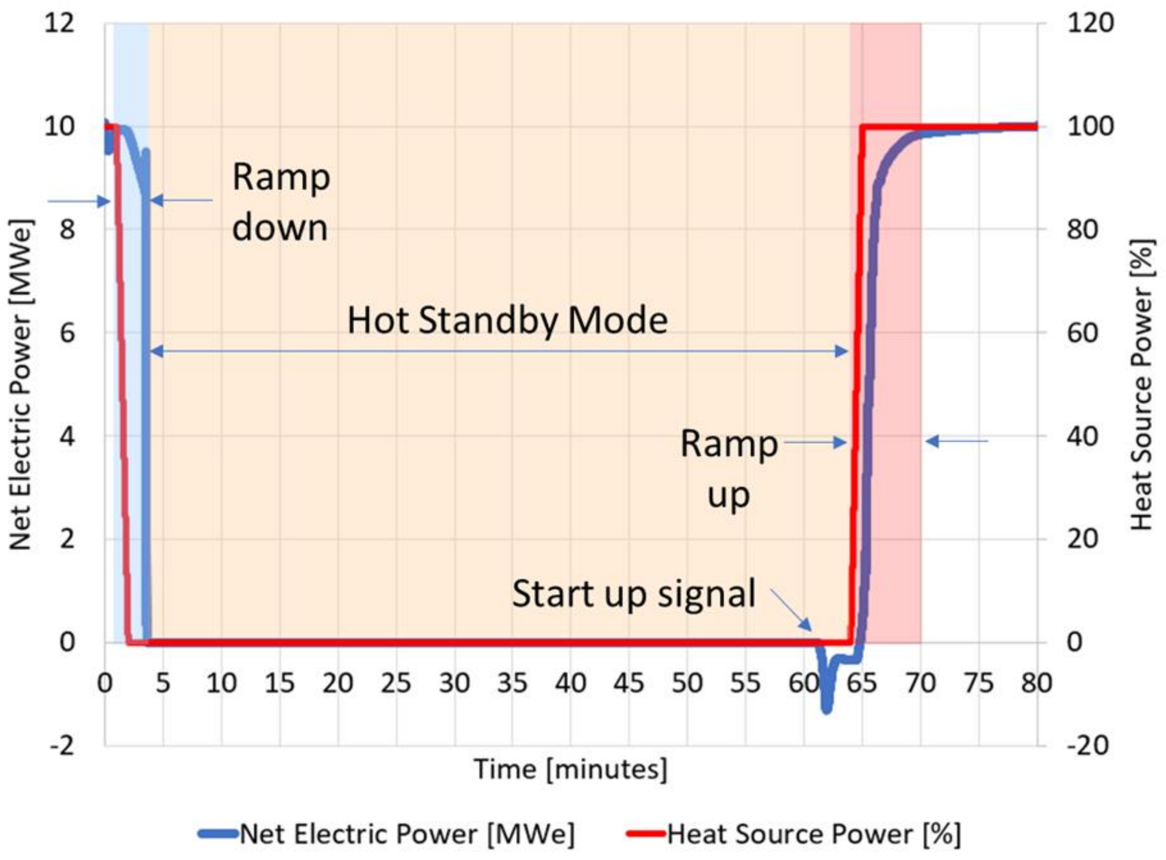
- **Status**
  - The dynamic model, using Flownex SE, is operational and used for:
    - Simulated Startup, Shutdown, Load Level Changes, and Emergency Shutdowns
    - HAZOP action items were simulated and reviewed to ensure no hardware limits were exceeded: Completed L1, L2 and L3 trip scenarios
- **Lessons Learned**
  - Startup: IMS Control used to manage peak flow, pressure while optimizing bypass cooler requirements
  - Shutdown: Shutdown Sequence tailored to keep HTR temperatures within limits and maintain stable compressor operation
- **Future Work**
  - The model will be updated as test data becomes available
    - Startup sequence will be validated with improved compressor maps
  - The Digital Simulator utilizes the dynamic model, and will be used to train individuals on how to operate the system without risk to the operators and facility

Simple Cycle Max: L2 Trip Analysis



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

- Study done on non-STEP funding evaluated STEP ramp rate capabilities
- Explored the ability of the sCO2 cycle to closely follow rapid startup & shutdown of a large-scale heat source
- sCO2 system shutdown and startups can take less than five minutes paced by the inertia of the rotating equipment
- Thermal transients at components were found to be acceptable
- Showed how the STEP dynamic simulation model is a valuable tool for powerplant design & evaluations



Heater

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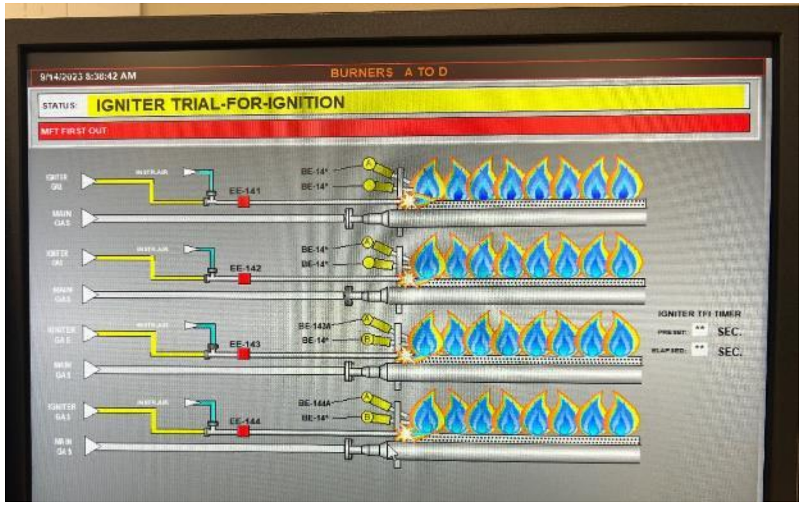
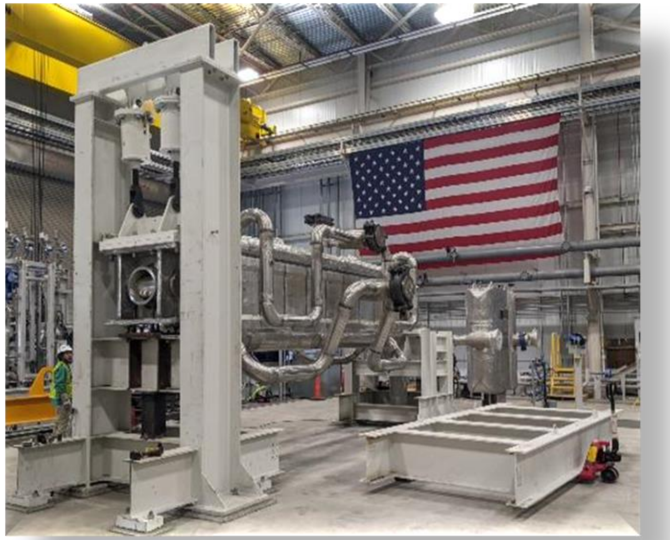
- **Status**
  - – Heater is mechanically complete
  - – Burnout completed with multiple light-offs and 4 hours of continuous operation
  - – SCR emissions control system installed and ready for commissioning and ammonia system tuning during full fire operation
- **Lessons Learned**
  - – How to better 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 instead of CO2 for heater burnout to accelerate schedule, but also provided safer work environment (no CO2)



Cooling Tower and Heat Exchangers

- **Status**
  - Cooling tower and main process cooler are operational and used to support compressor loop operation
  - High temperature recuperator (HTR) is installed
  - Low temperature recuperator was installed to support piping installation. It was then removed and set aside for future use in RCBC testing.
- **HTR lessons learned**
  - For sCO2 cycles, PCHE are more cost effective and compact than traditional shell and tube heat exchangers
  - For commercial scale plants, it may be better to incorporate multiple HTRs in parallel rather than scaling up the existing design
  - The ability of the HTR frame and anchors to resist tipping loads due to piping thermal growth should be addressed early in the design process


HTR

Cooling Tower


STEP Facility Piping

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- **Status**
  - Piping is complete, including insulation
  - Largely P91 and Inconel 740H
  - Believed to be largest installation of 740H in the world
- **Lessons Learned**
  - 740H was challenging to procure and install due to limited supply, material hardness and rigorous welding procedures required
    - Industry welding capabilities improved during the project with nearly 100% weld success in final 740H pipe installation
    - Skilled machinist with Inconel 740h experience and the use of carbide inserts improved bevel speed and quality
  - Caesar was a valuable tool to develop approaches for thermal growth mitigation and pipe support design