High Intensity Thermal Exchange through Materials and Manufacturing Processes
HITEMMP Annual Program Review Meeting - March 29 & 30 – Atlanta, GA

High Temperature, Recuperated sCO_2 Brayton Power System

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Project Vision

Sustainable and modular electric power generation that is efficient and cost effective with minimal environmental impact.

Key components:

High Temperature/Pressure Recuperator, Expander and Primary Heater

Brief Project Overview

Fed. funding:	$3.2M
Length	36 mo.

Team member	Location	Role in project
Thar Energy, LLC	Pittsburgh, PA	Modular Power system design, Component design and fabrication, System integration and testing

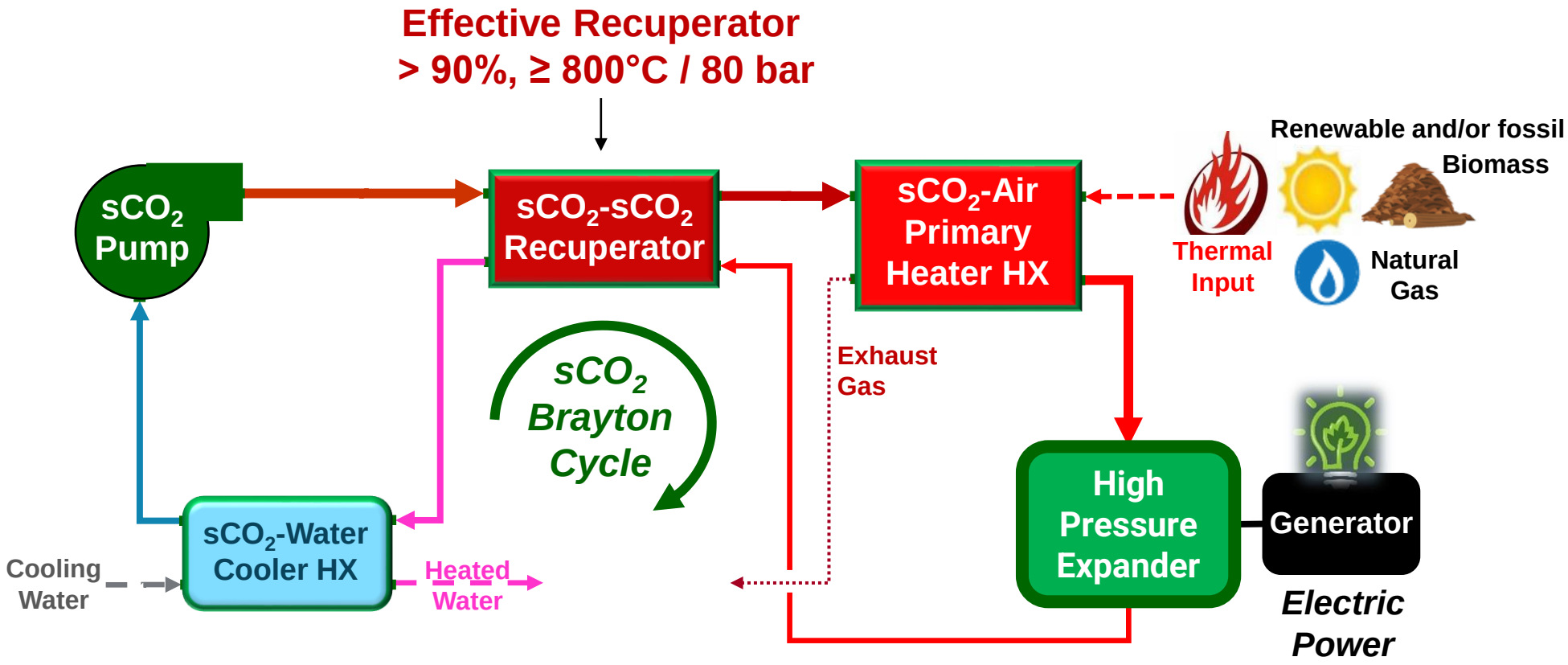
Thar has worked, with partners, to move the supercritical carbon dioxide (sCO_2) Brayton Power Cycle from *concept to hardware*.

Recent Past
Component Development & Testing
Power Cycle Analysis & Testing

Future
Power Systems Development & Testing

sCO_2 High Temperature Recuperated Brayton Power Cycle System

1 Stage



2-Stage System
Thermal efficiency > 50%

Progress Against Tasks – Timetable

Moving from component design/fabrication to system assembly/testing

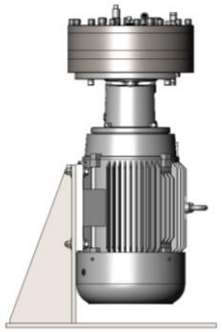
sCO_2 POWER CYCLE SYSTEM ANALYSIS
1-Stage Cycle & 2-Stage Cycle

- **Thermodynamic analysis**
- **Sensitivity analysis**
- **Cycle Efficiency vs.**
  - **Expander Inlet Temperature**
  - **Expander Inlet Pressure**
  - **Pump Isentropic Efficiency**
  - **Expander Isentropic Efficiency**
  - **Recuperator Pinch Point**
  - **System Pressure Drop**
- **System and Component Design**

- **Results:**
  - **1 stage – EIT 550°C, ~40% efficiency**
  - **2 stage – EIT 800°C, ~52% efficiency**

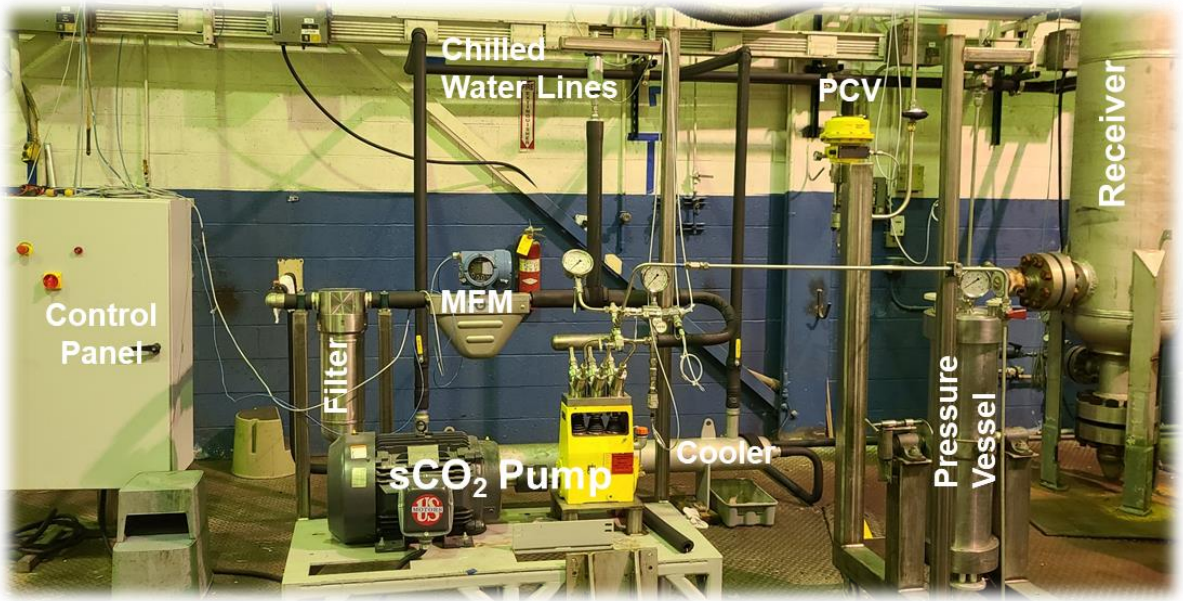
Component Design
1-Stage Cycle - Pump

- **High Speed sCO_2 Pump**
  - Down-selected pump concept
  - FEA performed
  - Design finalized
  - Pump fabricated and tested
  - Lessons learned incorporated
  - Pump being readied for 1-stage power block



sCO_2 Pump Test Stand

- **sCO_2 flow rates up to 60 kg/min**
- **Pressure up to 15,000 psi**

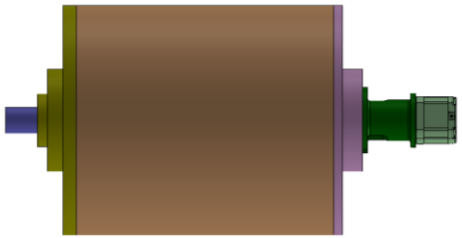


- **Expander component evaluation**
- **Pipe coupler/fitting evaluation**

Mass flowrate consistently exceeds design specifications.

Component Design
1-Stage Cycle - Expander

- **sCO_2 Expander**
  - ➢ Down-selected 1st expander concept
    - ○ New valve and seal concepts
    - ○ Abandoned concept – covid delay
  - ➢ Down-selected 2nd expander concept - **Axial Piston Expander**
    - ○ New bearing concept–discont.-covid delay
    - ○ Power end design/tests completed
    - ○ Valve design near completion
    - ○ Valve test rig design near completion
    - ○ Production drawings in process



Power-End Test Rig

- **Simulates acting forces on the pistons**
- **Cam rotated at 1800 RPM**
- **Component deformations/wear monitored**
- **Oil temperature recorded**

Component Design
1-Stage Cycle - Recuperator

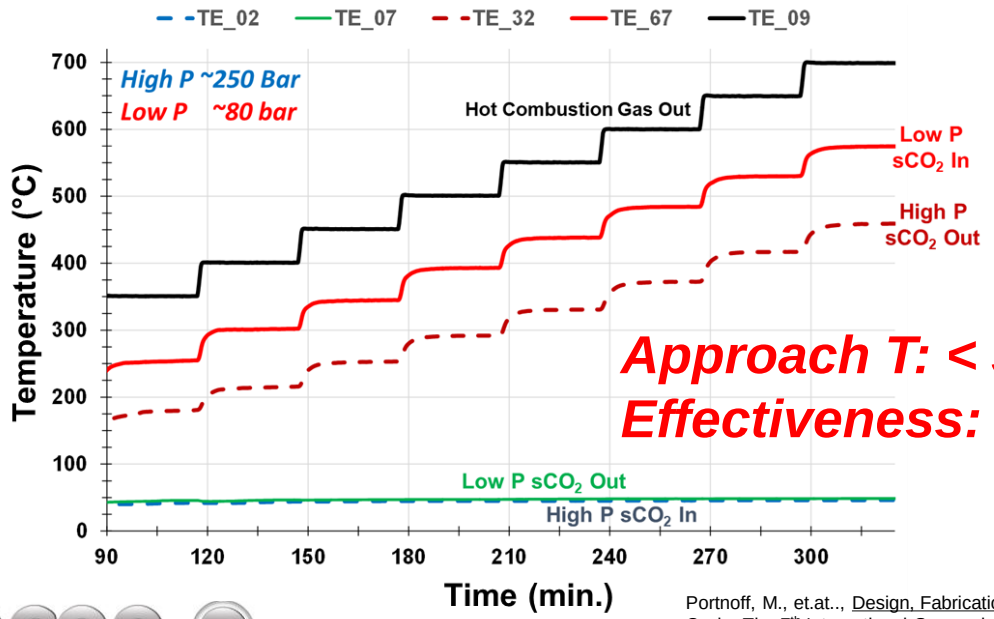
Recuperator (Laser-SSHX, 3D-SSHX, & Combo-SSHX)

- Evaluated for use in 1-Stage System – ***risk reduction***
- Additional testing performed
  - Data used to refine design/performance models
  - Thermal analysis perform - Laser-SSHX, 3D-SSHX & Combo-SSHX
- FEA performed for 1-stage conditions
  - Passed stress analysis

Laser-SSHX
347H SS

3D-SSHX
Inconel 625

Combo-SSHX Time vs. Temperature Plot



Approach T: < 5°C
Effectiveness: > 98%

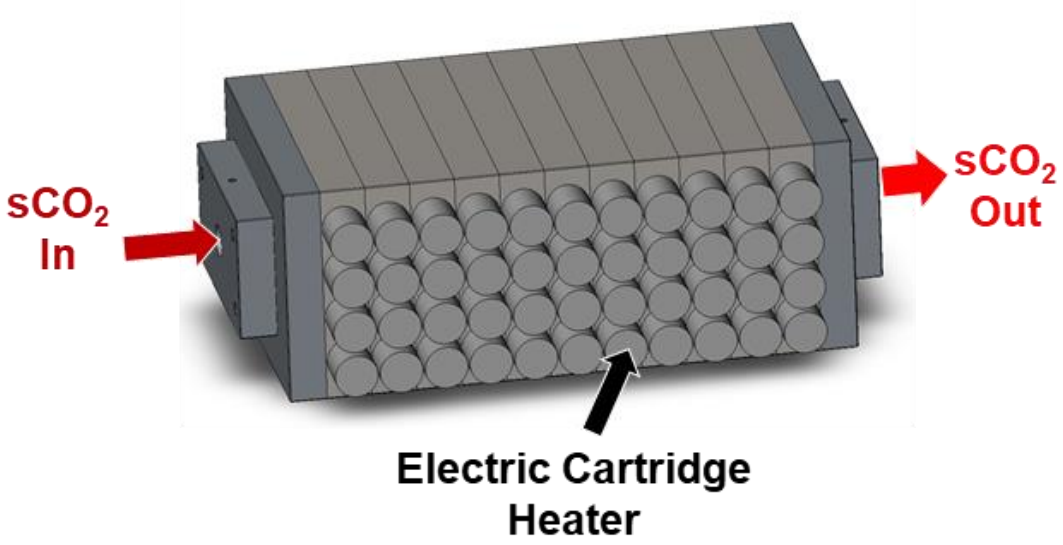
SSHX	Approach Temperature
1-Stage	5°C
Laser-SSHX	11°C
3D-SSHX	11°C
Combo	4°C

Reduced cycle efficiency

Portnoff, M., et.at.., Design, Fabrication and Testing of Novel Compact Recuperators for the Supercritical Carbon Dioxide Brayton Power Cycle, The 7th International Symposium-Supercritical CO_2 Power Cycles, February 23, 2022, San Antonio, TX

Component Design
1-Stage Cycle – Primary Heater & Water Cooler

- **Primary Heater** – ***risk reduction***
  - Designed for:
    - **1-Stage system**
    - **2-Stage system**
    - **HX Test Loop - Testing 800°C recuperator**
  - **Down-selected Electric heater**
    - Safer more compact design
    - SSHX fabrication method – H282
  - **FEA/CFD Performed**
  - **Design/Fabrication completed**
  - **Fittings fabricated & welded**
  - **Post weld heat treat & hydrotest scheduled**



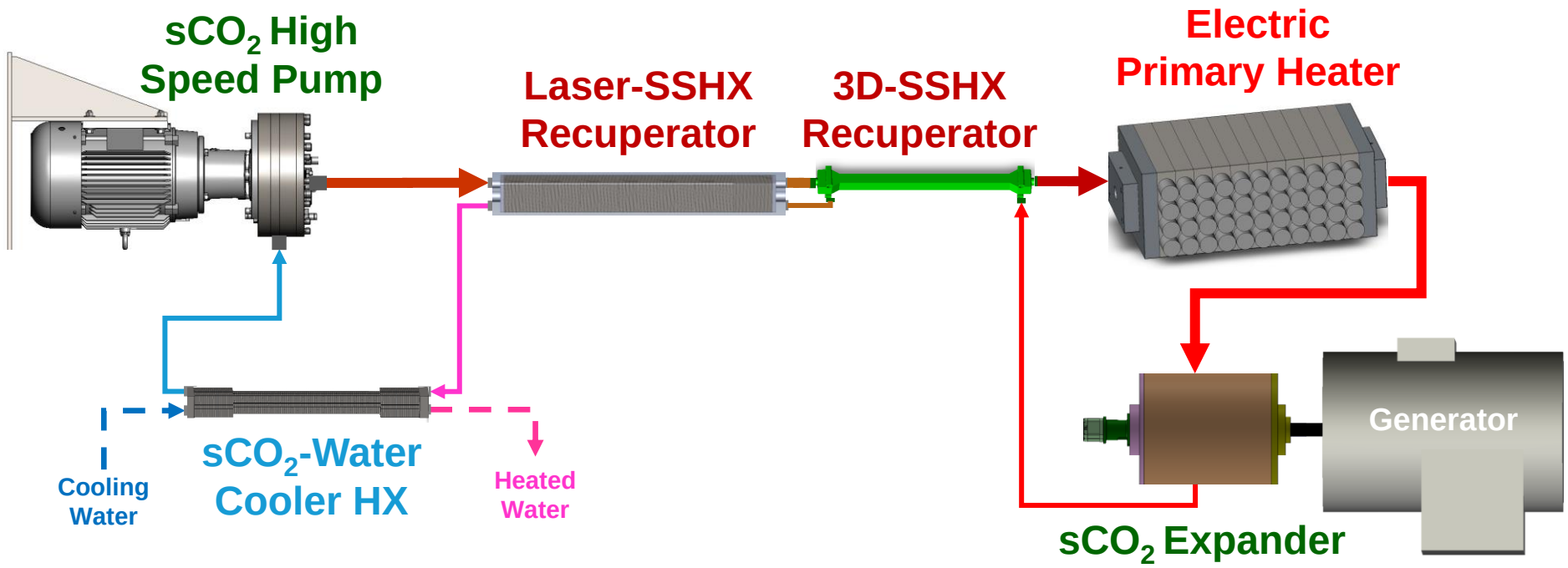
- **Water Cooler, 1-stage system**
  - Laser-SSHX design validated
  - QA/QC procedures validated
  - **Risk reduction**
    - Use commercial BPHE

Laser-SSHX, 316 SS

sCO_2 High Temperature Recuperated Brayton Power Cycle System

1 Stage – 25 kWe

Components Designed - P&ID and PFD issued



800°C Recuperator Performance Specifications

SSHX Recuperator meets/exceeds STEP criteria

APPA-E project goals

Criteria	S.T.E.P. State of Art Target	Thar SSHX Recuperator	ARPA-E Category A Target	Thar Project Goals
Thermal Effectiveness	97%	✓	≥ 80%	**> 95%**
Temperature Limit	577°C	✓	≥ 800°C	**> 800°C**
Low Pressure	85 bar	✓	≥ 80 bar	**≥ 80 bar**
High Pressure	255 bar	✓	≥ 250 bar	**≥ 300 bar**
Pressure Loss	$\Delta P_h < 1.5\%$	✓	$\Delta P_h < 2\%$	**$\Delta P_h < 2\%$**
	$\Delta P_c < 0.6\%$	✓	$\Delta P_c < 2\%$	**$\Delta P_c < 2\%$**
Cost	< $100 / kWt	✓	$2000/UA	**< $100/UA**

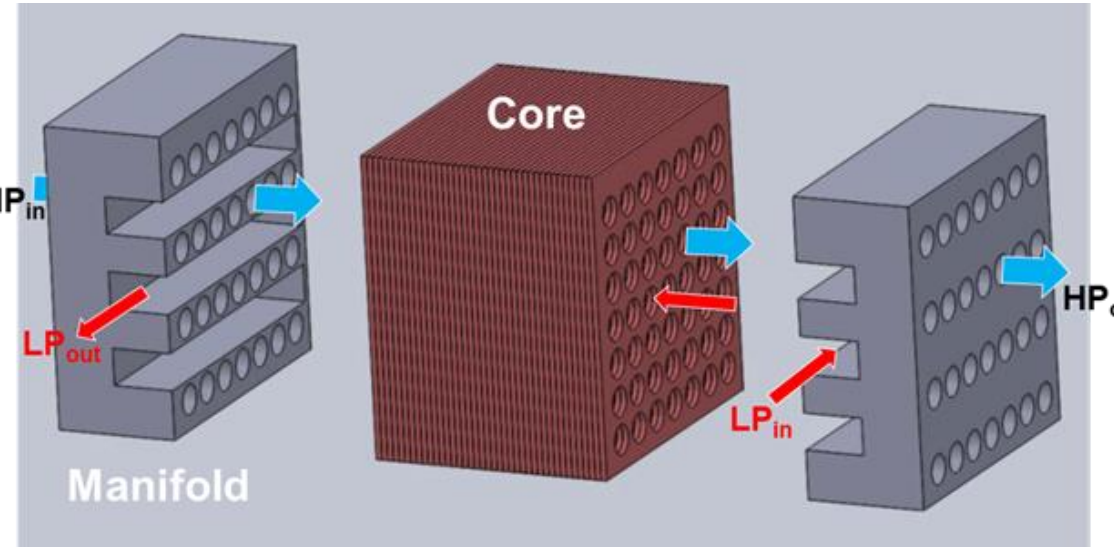
347H Stainless
Inconel 625

γ' strengthened Nickel Super-alloys

- **Design for use in 2-Stage system**

800°C Recuperator & 2-Stage Recuperator

Based on Thar's Stacked Sheet Heat Exchanger (SSHX) Recuperator Concept



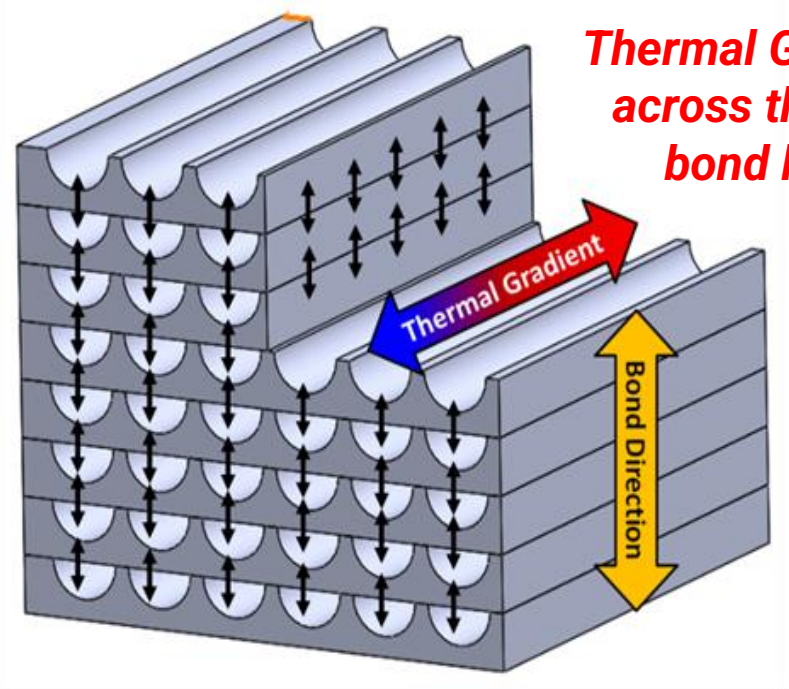
- Patterns cut, punched or etched into individual sheets
- Sheets are aligned, stacked and joined (brazed, diffusion bonded)
- Manifolds/headers are added to separate flow streams and ensure uniform flow distribution

Opportunity for cost effective design enhancements

Accommodates digital advances in Subtractive and/or Additive Manufacturing

CASE STUDY

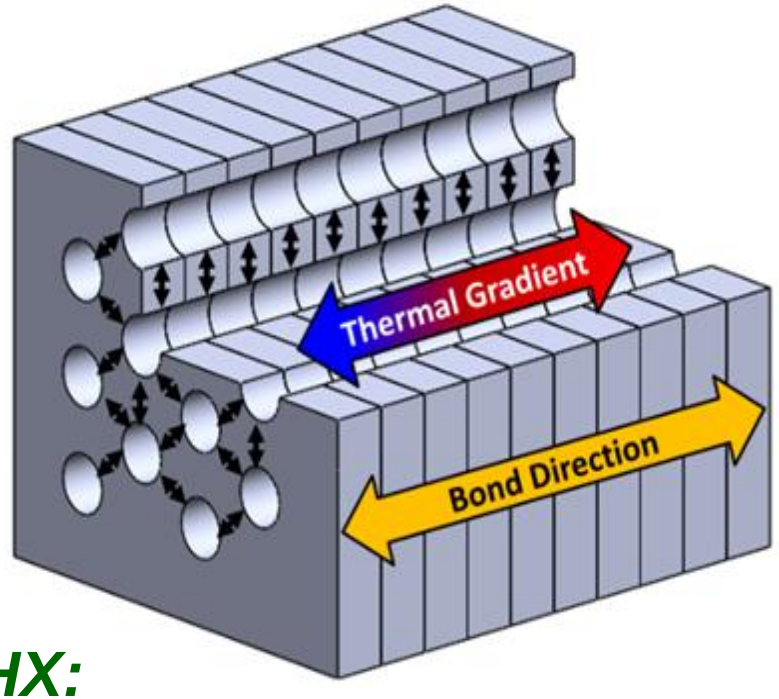
SSHX and Printed-Circuit HX Mechanical & Thermal Stress Analysis



Thermal Gradient is across the entire bond length

Printed-Circuit HX:

The bond between sheets is:
perpendicular to the mechanical stresses &
parallel to the thermal stresses



SSHX:

The bond between sheets is:
parallel to the mechanical stresses &
perpendicular to the thermal stresses

Improves structural integrity and thermal compliance

800°C Recuperator & 2-Stage Recuperator

H282 3D-SSHX Recuperator Update

- H282 3D printed parts validated
- H282 braze process confirmed
  - 3D printed & Machined parts
- FEA & CFD analysis performed
- H282 3D-SSHX Recuperator design completed
- Fabrication completed
- Fittings fabricated and welded
- Post weld heat treat & hydrotest scheduled

Braze tensile test at 815°C

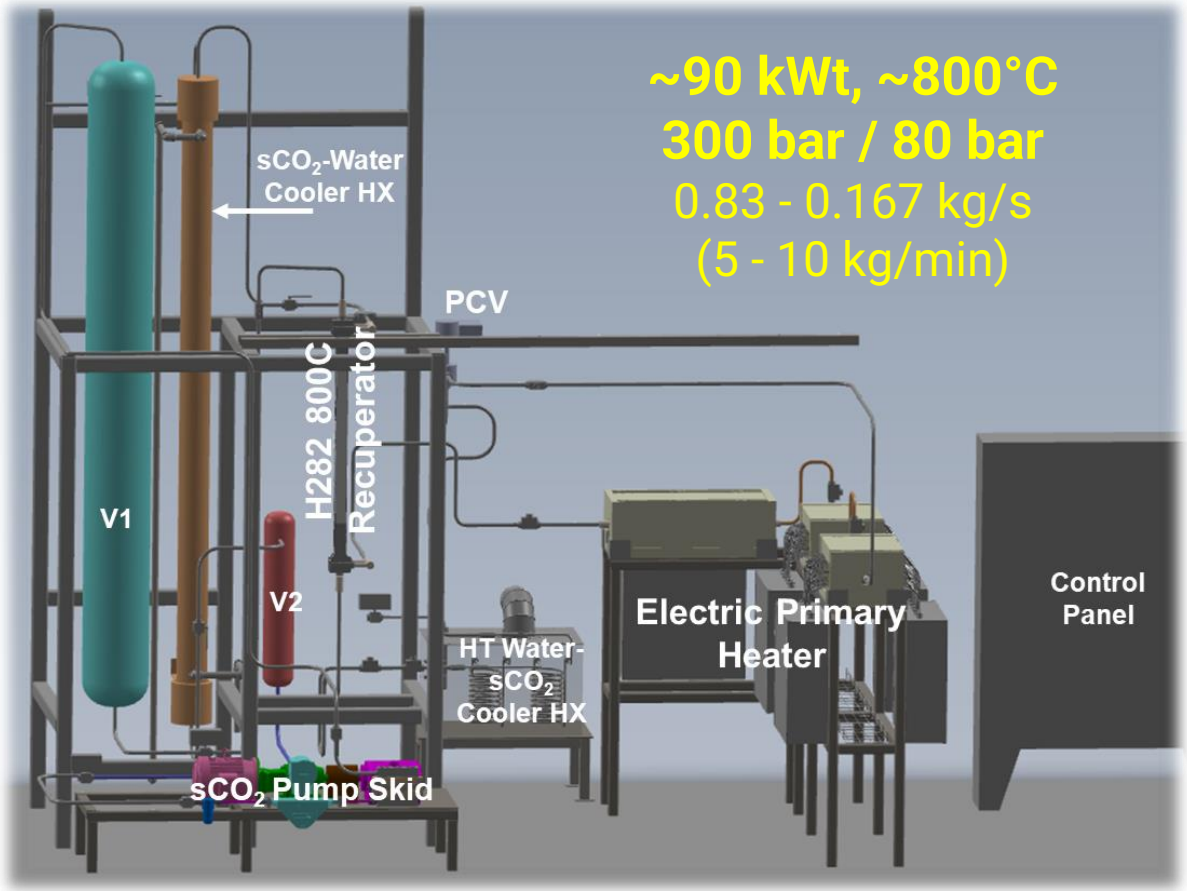
- UTS: avg. 90% of base metal
- YS: avg. 93% of base metal

Solid Model

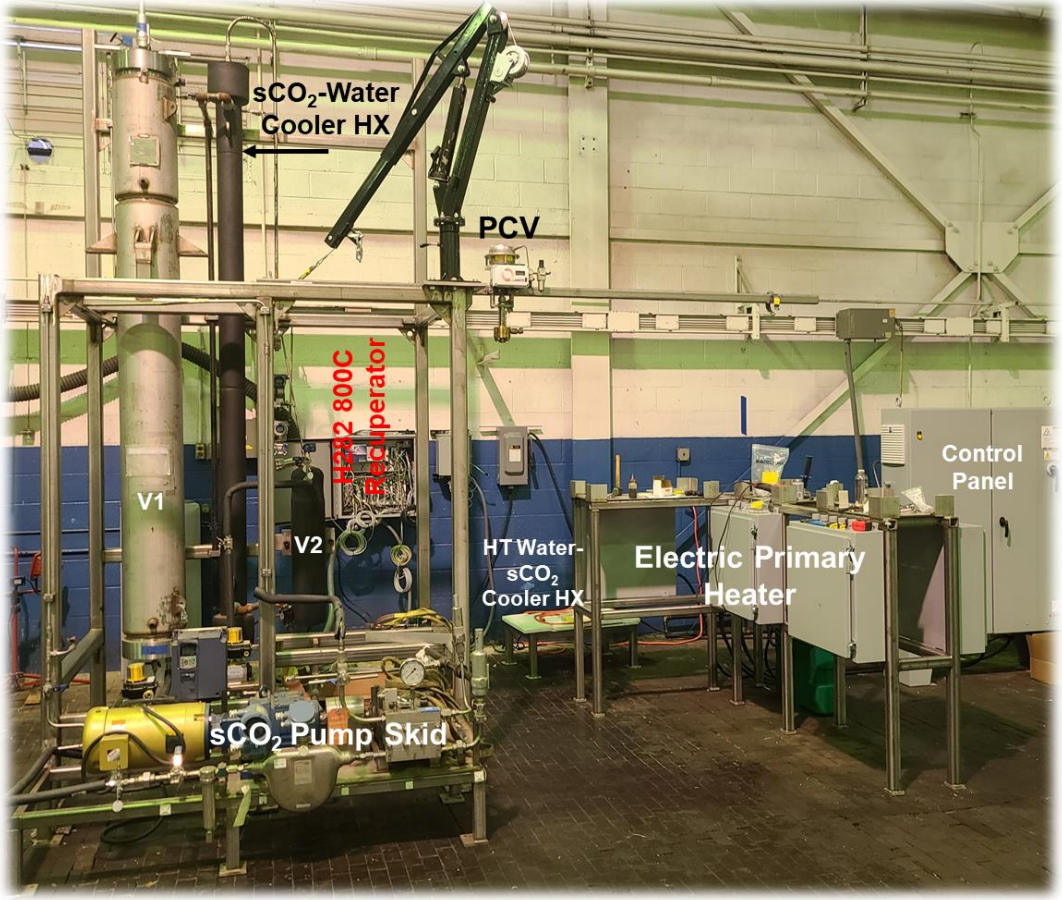
High Temperature HX Test Loop

Design complete and under construction

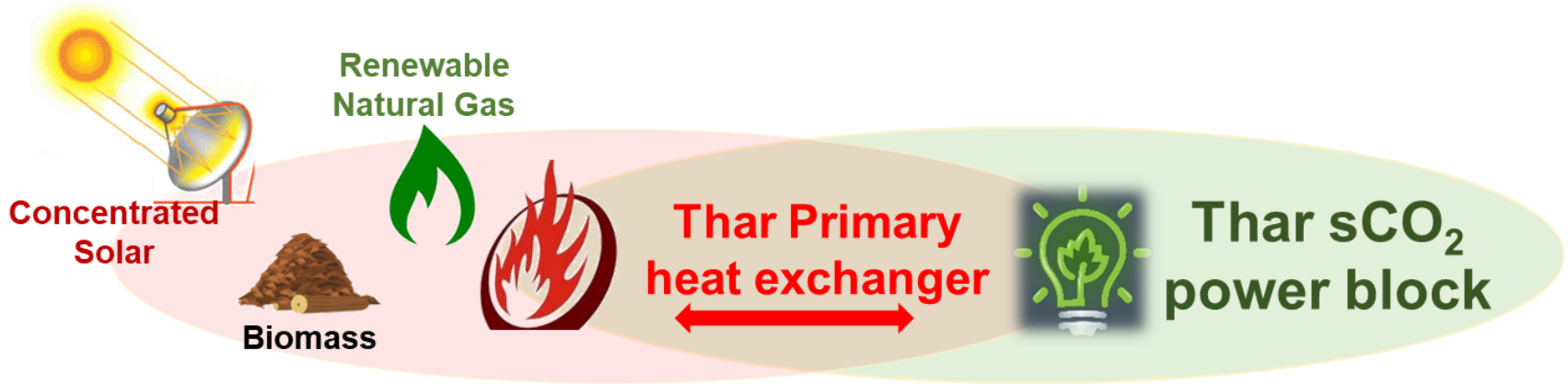
System Layout



High Temperature HX Test Loop



Technology-to-Market Update

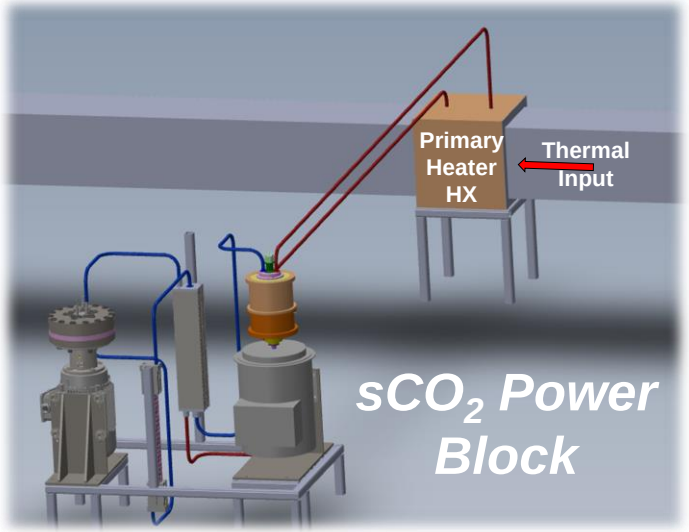


You bring the heat! **We provide the power!**

Business cases recently updated

- Competitor technology benchmarked for performance & cost
- Market size impacted by ease & cost of installation
- *200 kWe 1-stage sCO_2 power block competitive at ~1,500 $/kWe*

Thar Energy's CHP sCO_2 Power Block



- ***Efficient***
  - Elec. Efficiency: >40%
  - CHP Efficiency: >70%
- ***Modular & compact***
- ***Low cost of ownership***
- ***Reduced environmental impact***

Thank you for your kind attention!

Q & A

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Work supported by US DOE/ARPA-E under DE-AR0001129
Zak Fang, PhD, Program Director
Vivien Lecoustre, PhD & Rakesh Radhakrishnan, PhD

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