2018 UNIVERSITY TURBINE SYSTEMS RESEARCH PROJECT REVIEW MEETING

Embry-Riddle Aeronautical University

Daytona Beach, Florida
October 31, 2018

Development of Modular, Low-Cost, High-Temperature Recuperators for the sCO_2 Power Cycles – Project Update

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Thar Energy

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SwRI

DE-FE0026273

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Outline

- Introduction to Thar Energy

- Project Overview
    - Objectives
    - Participants
    - Task Summary

- Project Recap
    - STEP Recuperator Criteria
    - Recuperator Concept Down Select
    - Scaling Considerations

- Project Update
    - Prototype Design & Fabrication
    - Prototype Performance Testing

- Project Summary

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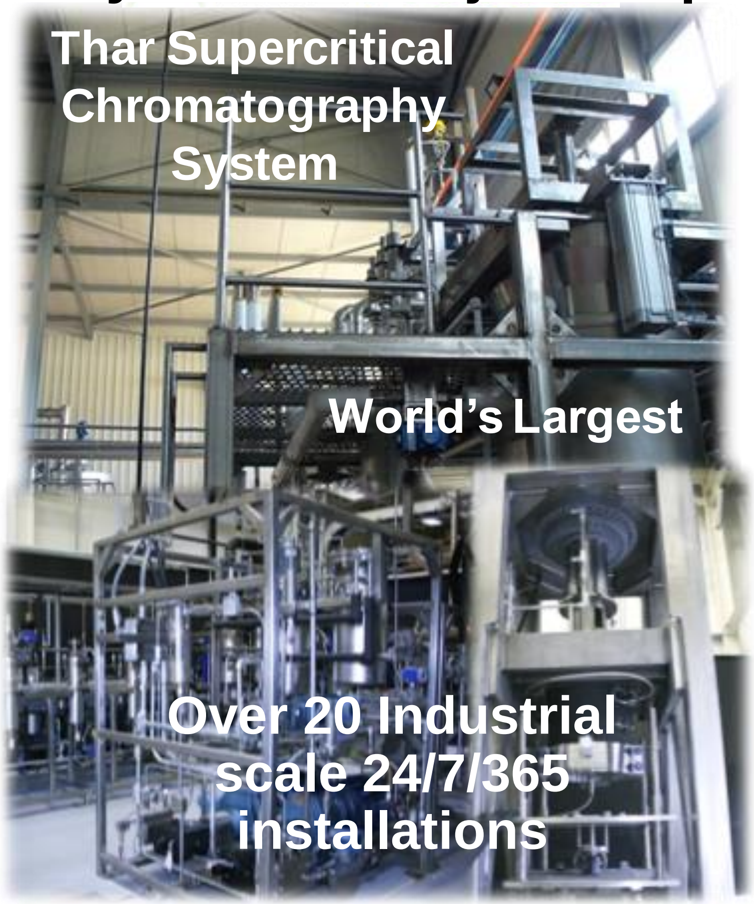
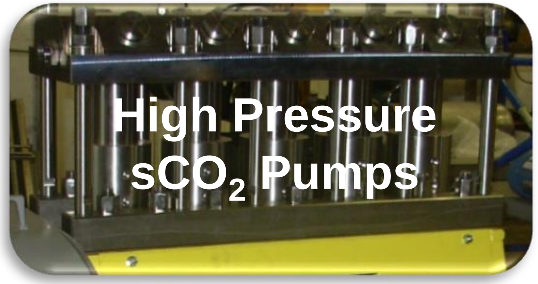
The Thar Brand - Over 25 years of Innovation with "Green" Supercritical Fluid Technologies

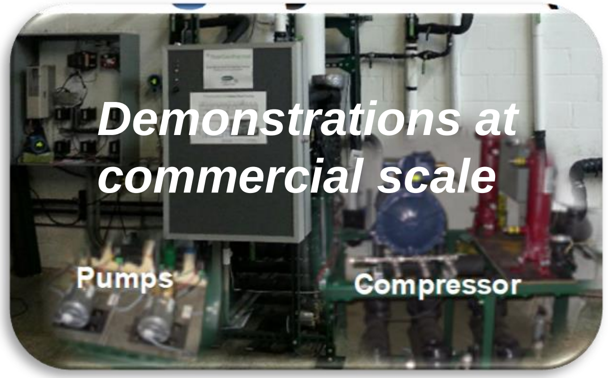
Design and commercialization of supercritical systems & major components





Over 5,000 scientific instruments installed

Direct Exchange, R744 (CO_2) Geothermal Heating & Cooling



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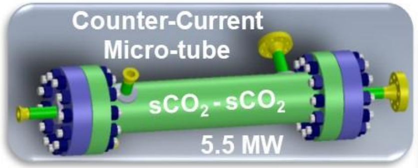
Thar Timeline (cont.)

sCO_2 Brayton Power Cycle Development

COMPACT Heat Exchangers for sCO_2 Power Cycles



3D Printed,
Inconel 718,
sCO_2-sCO_2
Recuperator

Design – Construct – Install
Primary Heater for Sunshot
One MWe sCO_2 Test Loop

Design – Construct – Operate
sCO_2 Heat Exchanger Test Loop
Superior Thermal Performance Confirmed

Gas
Cooler
Air-sCO_2

2014

TharProcess

Design – Construct –
Operate Largest GMP
sCO_2 Extraction
System in USA

2015

Expands into Liquid Chromatography

2016

Oxy Combustion Test Facility
Design – Construct – Operate
Demonstrate auto-combustion

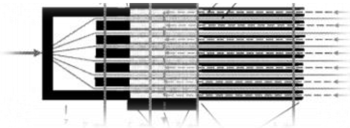
Thar Pharmaceuticals
sold to
GRUNENTHAL

2017

UNITED STATES PATENT AND TRADEMARK OFFICE

Patent - Notice
of Allowance

Counter Current Heat
Exchanger/Reactor



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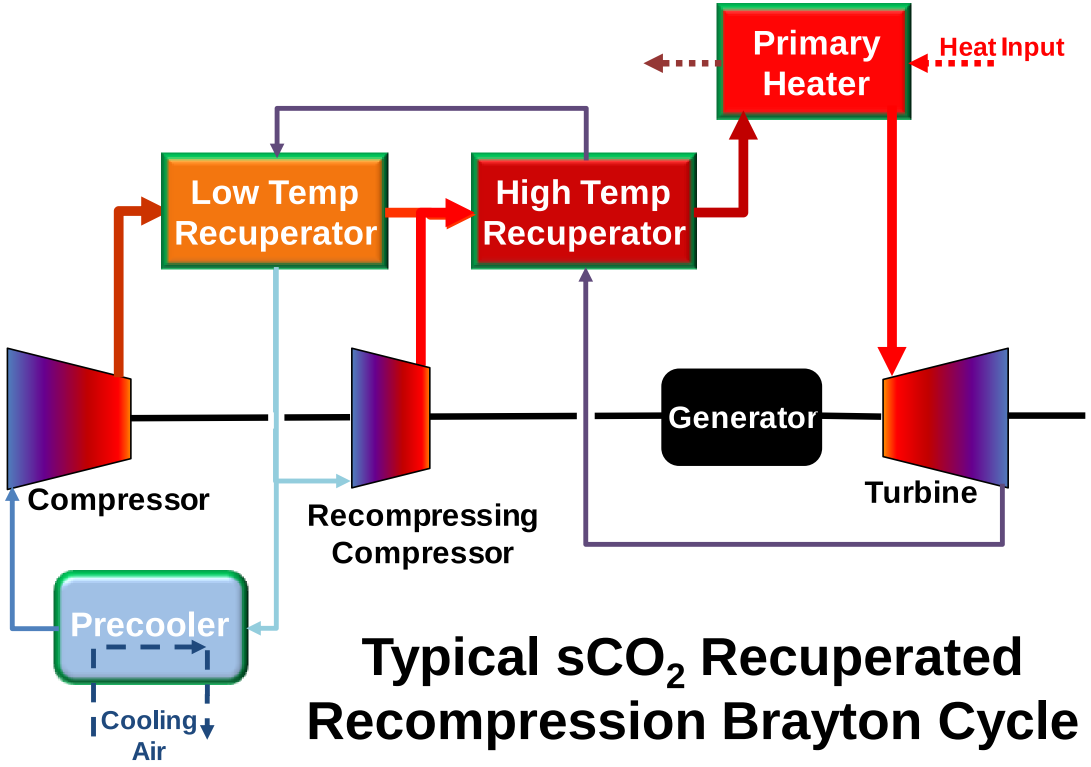
Heat Exchangers are key to improving sCO_2 power cycle efficiency and costs

Thar Energy - Manufacturer of *COMPACT* Heat Exchangers for sCO_2 Power Cycles

- **Recuperators**
- **Heaters**
- **Gas Coolers**
- **Water Coolers**

kWt to MWt



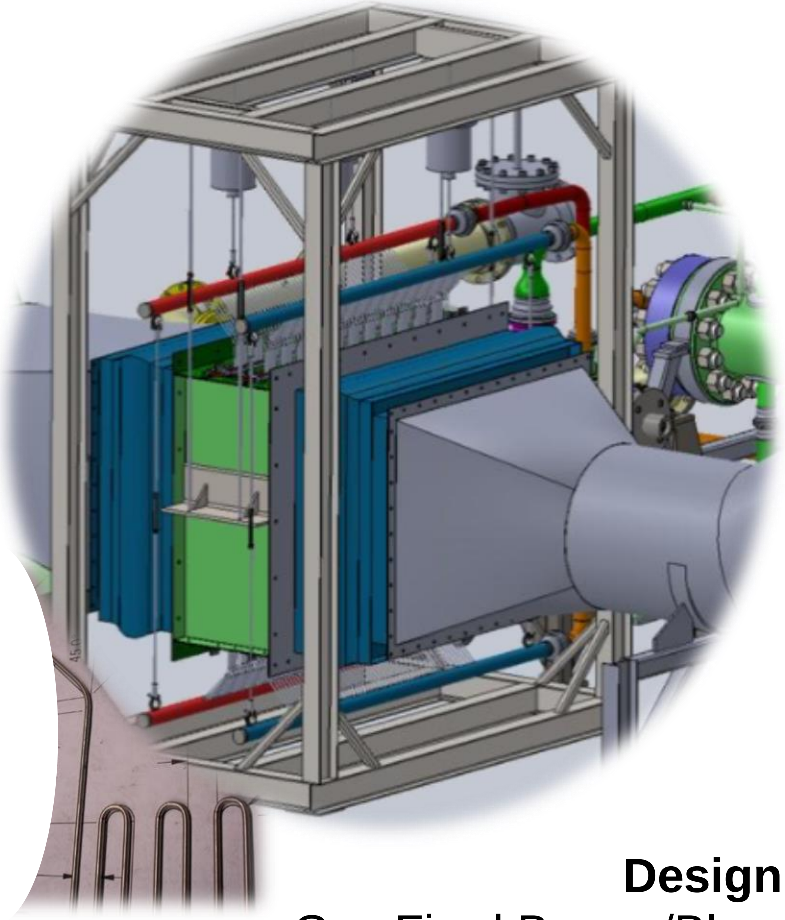
Typical sCO_2 Recuperated Recompression Brayton Cycle

Optimized Material Use

- *Aluminum*
- *Carbon Steel*
- *Alloy Steel*
- *Stainless Steels*
- *Nickel Super Alloys*

Sunshot Primary Heater HX Design – 2.5 MWt

Hot Gas to sCO_2 HX
Inconel 740H Construction



Design Conditions:

Gas Fired Burner/Blower Outlet Temperature: 870°C

sCO_2 Outlet Temperature: 715°C @ 255 bar

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Installed at SwRI

Thar Energy's sCO_2 Primary Heater

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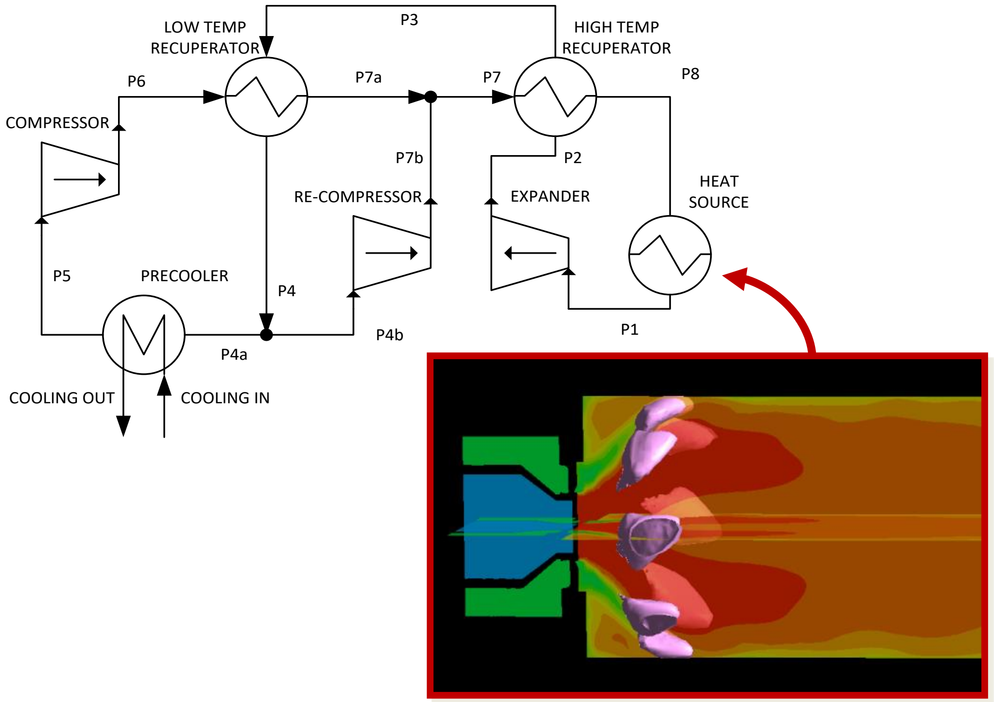
Direct Fired Oxy-Fuel Combustor for sCO_2 Power Cycles

Oxy-Combustion

- High Cycle Efficiency
- Combustion occurs in the working fluid
- Facilitates integrated carbon capture
- Water separation
- Compatible with dry cooling techniques
- Requires compact and efficient oxygen separation

1 MWt Demonstration Test Facility



Project Partners:

- Southwest Research Institute
- Georgia Tech
- Univeristy of Central Florida
- GE-GRC
- US DOE, DE-FE002401

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Project Overview

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Objective:

- **Advance** high-temperature, high-differential-pressure recuperator technologies suitable for use in sCO_2 Recompression Brayton Cycle (RCBC)

- **Evaluate, advance, and demonstrate recuperator concepts, materials, and fabrication methods** that facilitate the commercial availability of **compact and low cost recuperators** for RCBC conditions (e.g. turbine inlet temperatures exceeding 700°C, and differential pressures on the order of 200 bar)

- Emphasis placed on **scalable solutions** able to accommodate plant sizes from 10 - 1,000 MWe

Program will:

(1) Address critical design, materials, and fabrication challenges
(2) Significant impact on recuperator cost, performance, and scalability

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Project Participants

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Grant Musgrove, Klaus Brun, Stefan Cich, C.J. Nolen, Anthony Costanzo, Kevin Hoopes, Shane Coogan, Griffin Beck, Larry Miller, Melissa Poerner, Matt James, Josh Schmitt, Elliott Bryner, Fang Pan, Nick Mueschke, David Ransom

Bruce Pint

Devesh Ranjan, Sandeep Pidaparti

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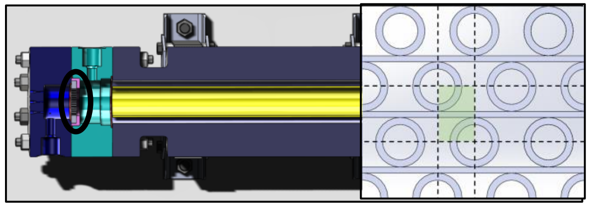
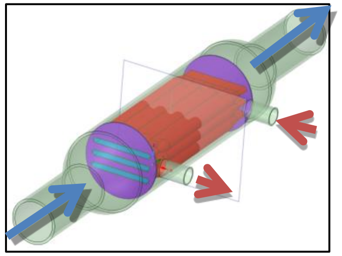
SOPO Tasks

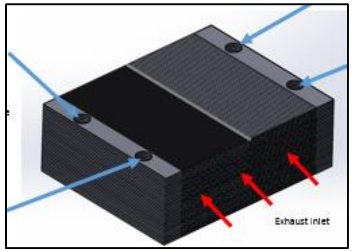
A <u>scaled prototype</u> will verify the design process and technology before designing for 47 MWt

Task 1.0 **Project Management and Planning**

Task 2.0 **Engineering Assessment of Advanced Recuperator Concepts**







Other Concepts from brainstorm

Techno-Economic Analysis for selected recuperator concepts

Task 3.0 **Preliminary design (detail design of 100 kWt prototype)**

Task 4.0 **100 kWt prototype fabrication and testing**

Go/No-Go Milestone for Budget Period 2

Task 5.0 **Detail design of 47 MWt recuperator**

Task 6.0 **Fabrication of 47 MWt recuperator**

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Project Recap

- STEP Recuperator Criteria
- Recuperator Concept Down Select
- Scaling Considerations

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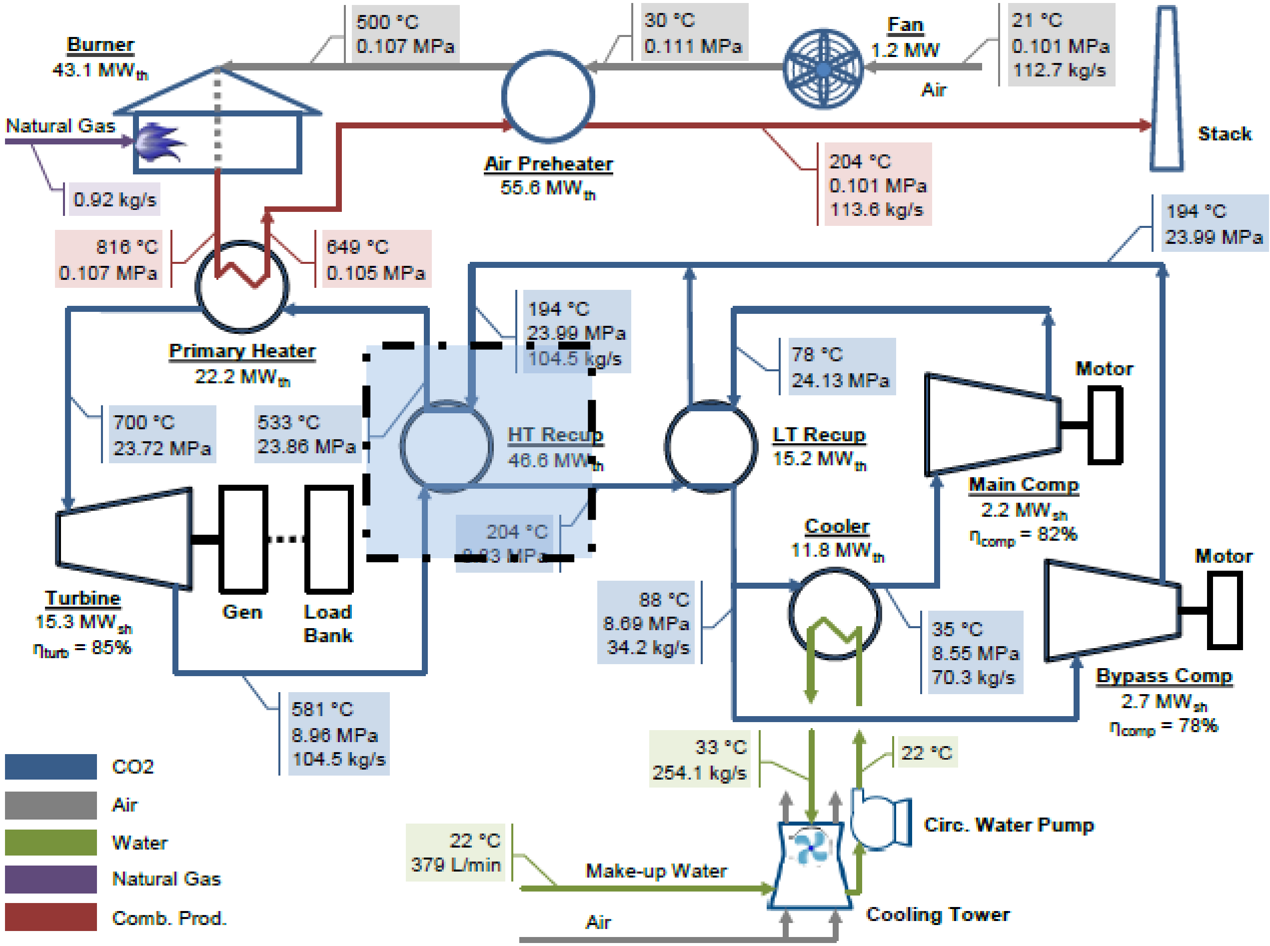
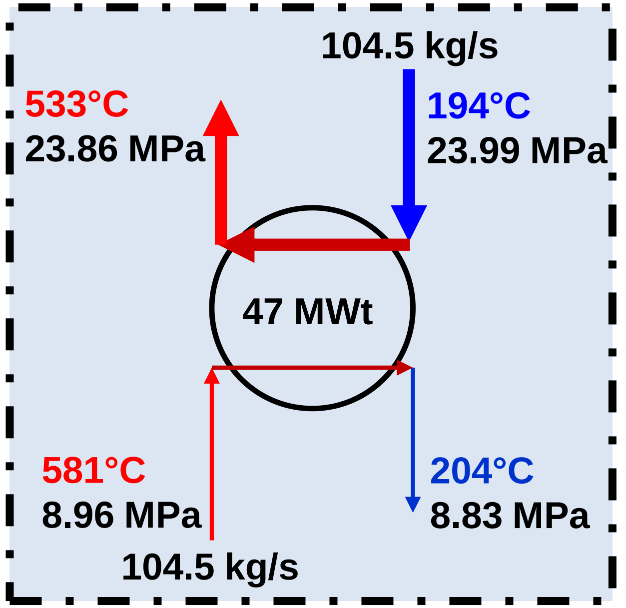
Develop a Scalable, High Temperature Recuperator for STEP Conditions



High Temperature Recuperator

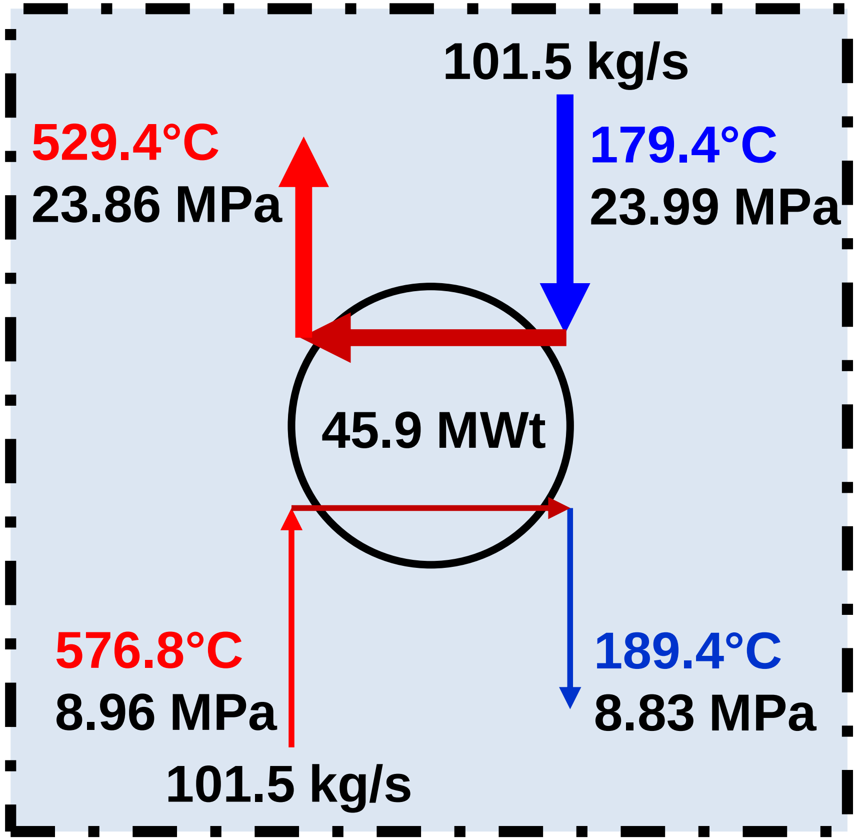


Updated STEP Cycle Conditions – 8/18/16

STEP sCO_2 Cycle Assumptions:

- Net electric power output = 10 MWe
- Turbine efficiency = 85%
- Generator efficiency = 98.5%
- Main Compressor efficiency = 82%
- Bypass Compressor efficiency = 78%
- Compressor Motor efficiency = 96.5%
- HX pressure drop/pass = 138 kPa
- Temperature approach = 10°C
- Mass flow = 101.5 kg/s

High Temperature Recuperator



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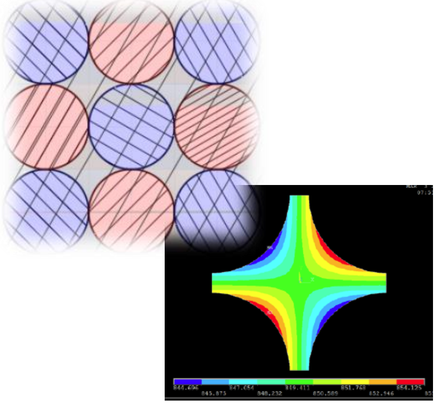
Comparison of Recuperator Design Criteria

Criteria	Initial	Updated
Thermal Capacity	**46.6 MWt**	**45.9 MWt**
Thermal Effectiveness	**96%**	**97%**
Pressure Loss	ΔP_h < 1.5% (1.3 bar) ΔP_c < 0.6% (1.3 bar)	
Temperature Limit	**581°C**	**577°C**
Differential Pressure	152 bar	
Life	30,000 hr	
Cost	< $100 / kWt	
Package Dimensions	8.8 x 3.6 x 2.6 m	

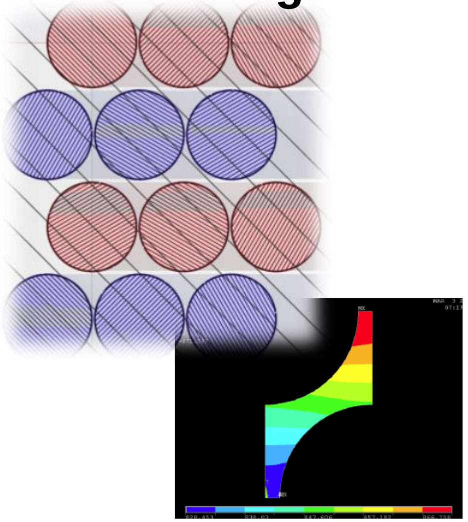
Heat Exchanger Design

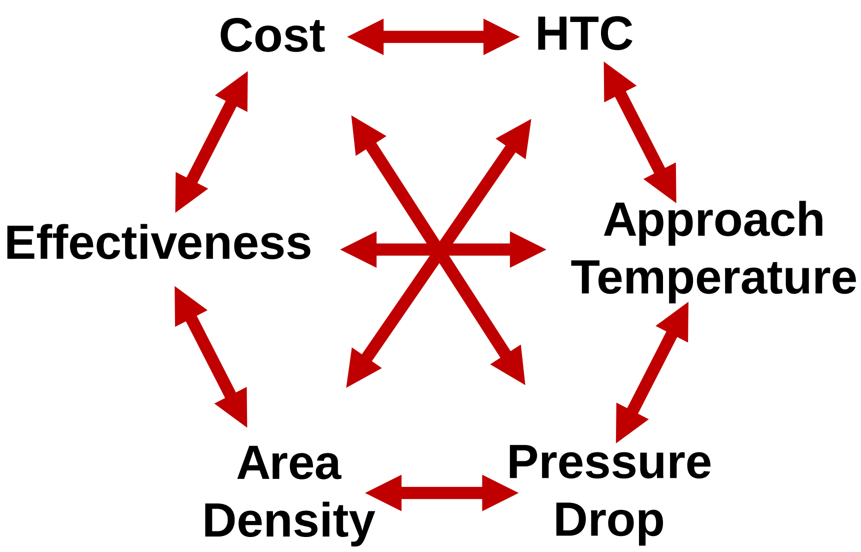
- Area Density (Microchannel passage size)
- Counter Current flow
- Checker Board Flow Pattern
- Passage Shape
- Surface Effects
- Turbulent vs Laminar flow

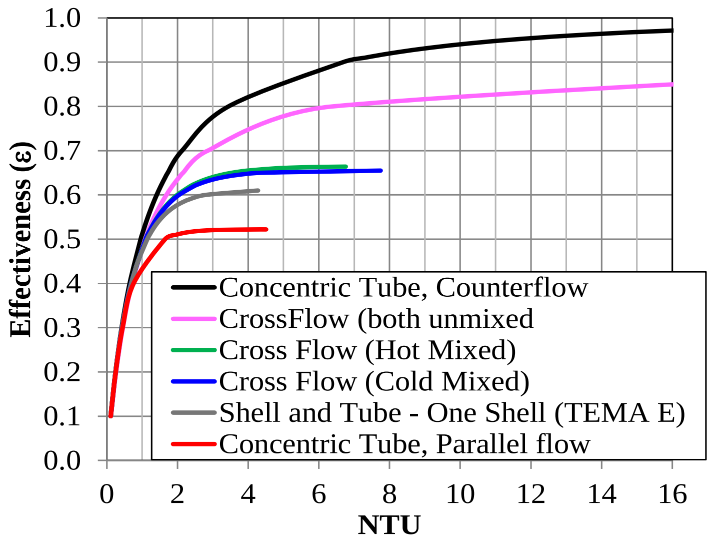
Checkerboard



Alternating Rows







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First Cost vs Life Cycle Costs

- Smaller passages are more susceptible to plugging, fouling and are harder to maintain
- Lower cost alloys can be more susceptible to corrosion
- HX design susceptibility to thermal fatigue at scale

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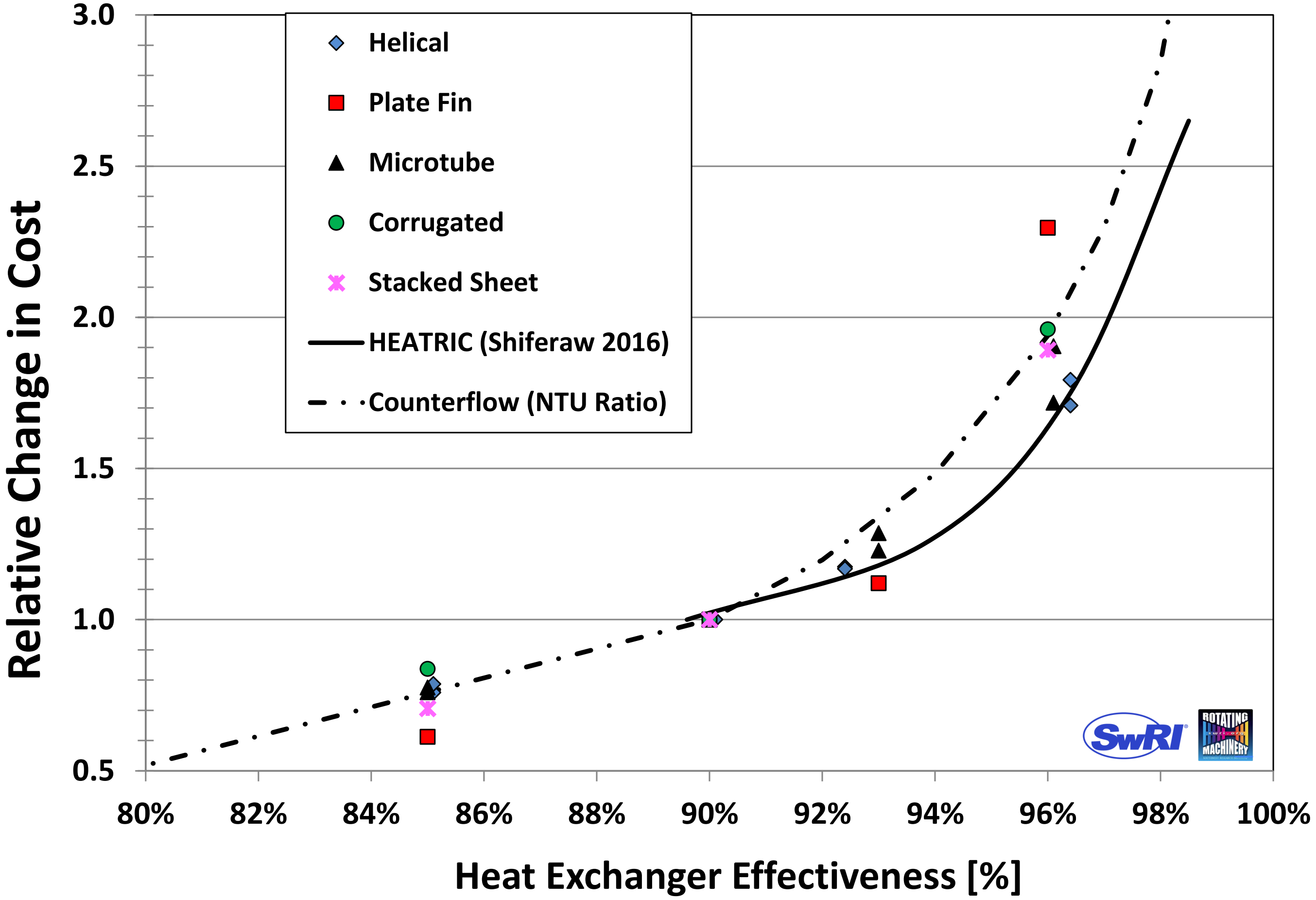
Recuperator specifications influence cost

Relatively independent for the heat exchanger concepts evaluated

- Approach Temperature
- Effectiveness

- Pressure Drop
- Mass Flow

- Pressure
- Temperature



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Recuperator Design

Thermal capacity
Effectiveness
Pressure drop
Design T & P
Size (L X W X H)

Fluid Stream 2
T, P, Mass Flow

Fluid Stream 1
T, P, Mass Flow

Material of Construction

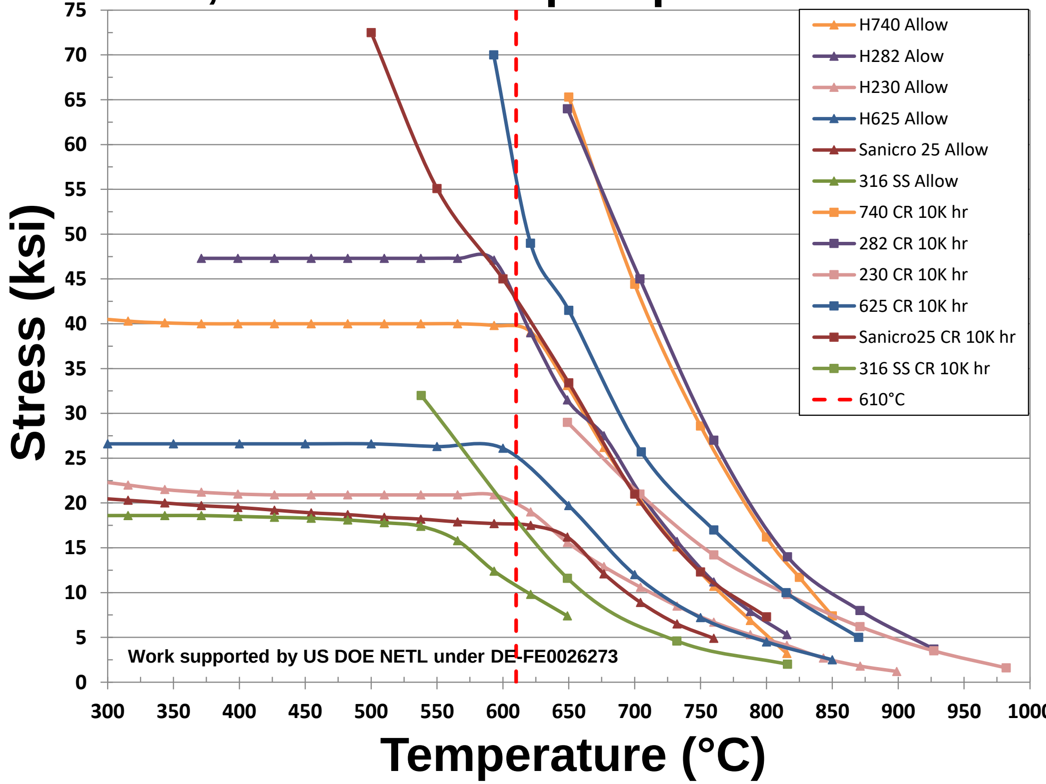
- Physical Properties
- Corrosion
- Contamination potential

ASME Code Stamp/Design

Fouling Factor

Goal: Meet performance requirements and provide margin of safety while minimizing over design

ASME Allowable Stress and 10,000 Hour Creep Rupture Values



Design T ***$***

As Design T increases, the material strength drops & corrosion rates increase

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Recuperator Temperature & Pressure Rated Design Points

Condition	Temp. (°C)	Pres. (bar)	Comment	
Operating Point	581	240	from Step facility process schematic	
Rated Design Pt. 1	591	264	T+10°C,	P+10%
Rated Design Pt. 2	**611**	**280**	T+30°C (~5%),	P+ 5% + PSV setting
Rated Design Pt. 3	640	293	T+10%,	P+10% + PSV setting

Guidance provided by ASME and Industrial Standards (e.g. NORSOK)

Team Recommendation: Rated Design Point 2

Provides a margin of safety with minimum over design.

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State-of-the-art sCO_2 HX were reviewed in detail

Project criteria:

47MWt, 240 bar, 581°C, 96% Effectiveness, ΔP < 1.3 bar, <$100/kWt

***Insufficient information in the literature* to demonstrate state-of-the-art sCO_2 HX could meet cost specification**

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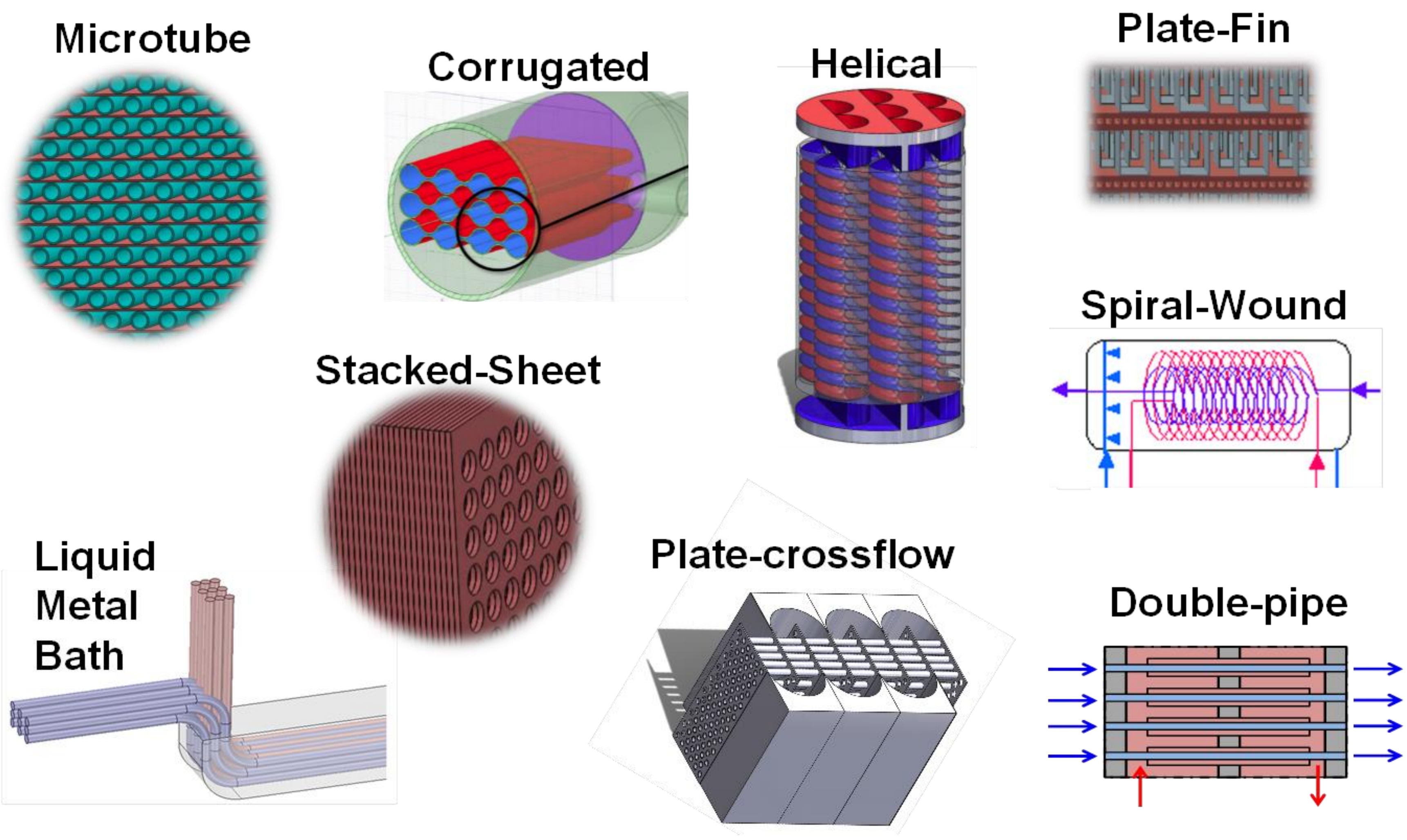
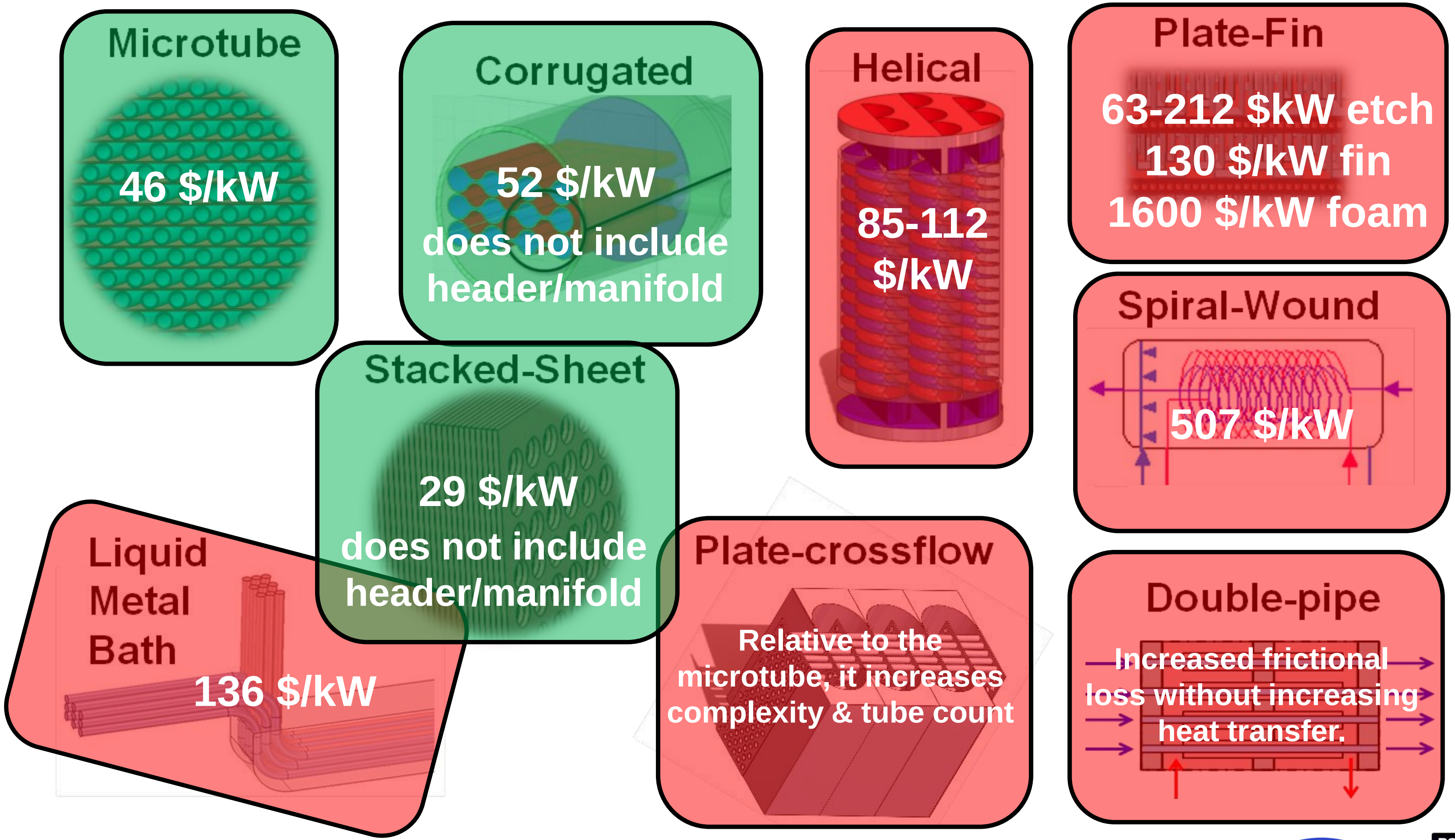
Recuperator Concepts Selected from Brain Storming



The Microtube, Corrugated & Stacked-Sheet Recuperator Concepts were *down selected* for low complexity and cost

47MWt, 240 bar, 581°C, 96% Effectiveness, ΔP < 1.3 bar, <$100/kWt



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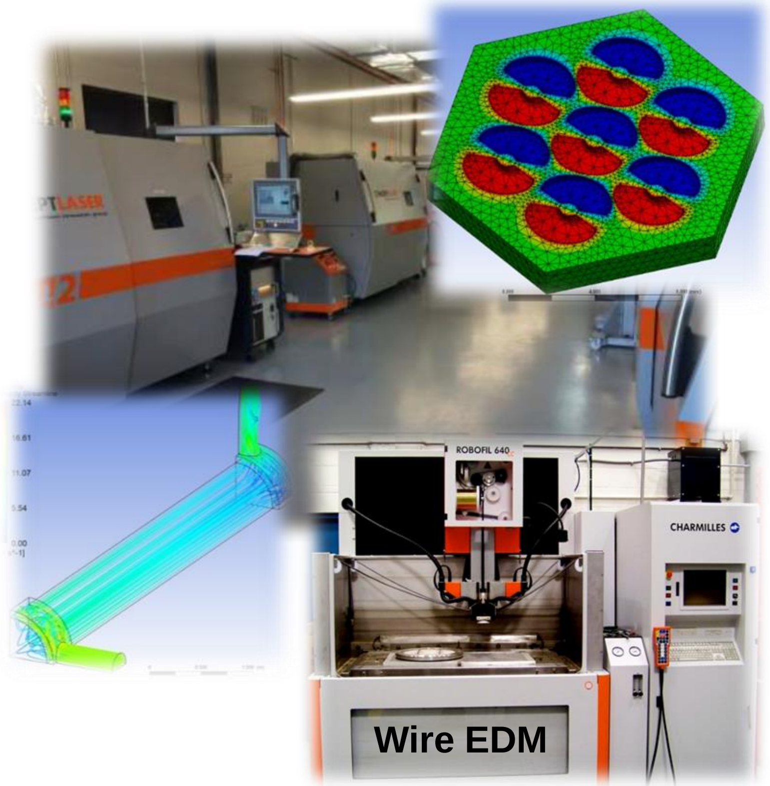
HTR Recuperator Concepts
Engineering Analysis & Down Select

- Thermal-Hydraulic performance modeling and analysis
- Advanced manufacturing methods and tolerance
- Fabrication cost analysis

Subtractive vs. Additive Manufacturing

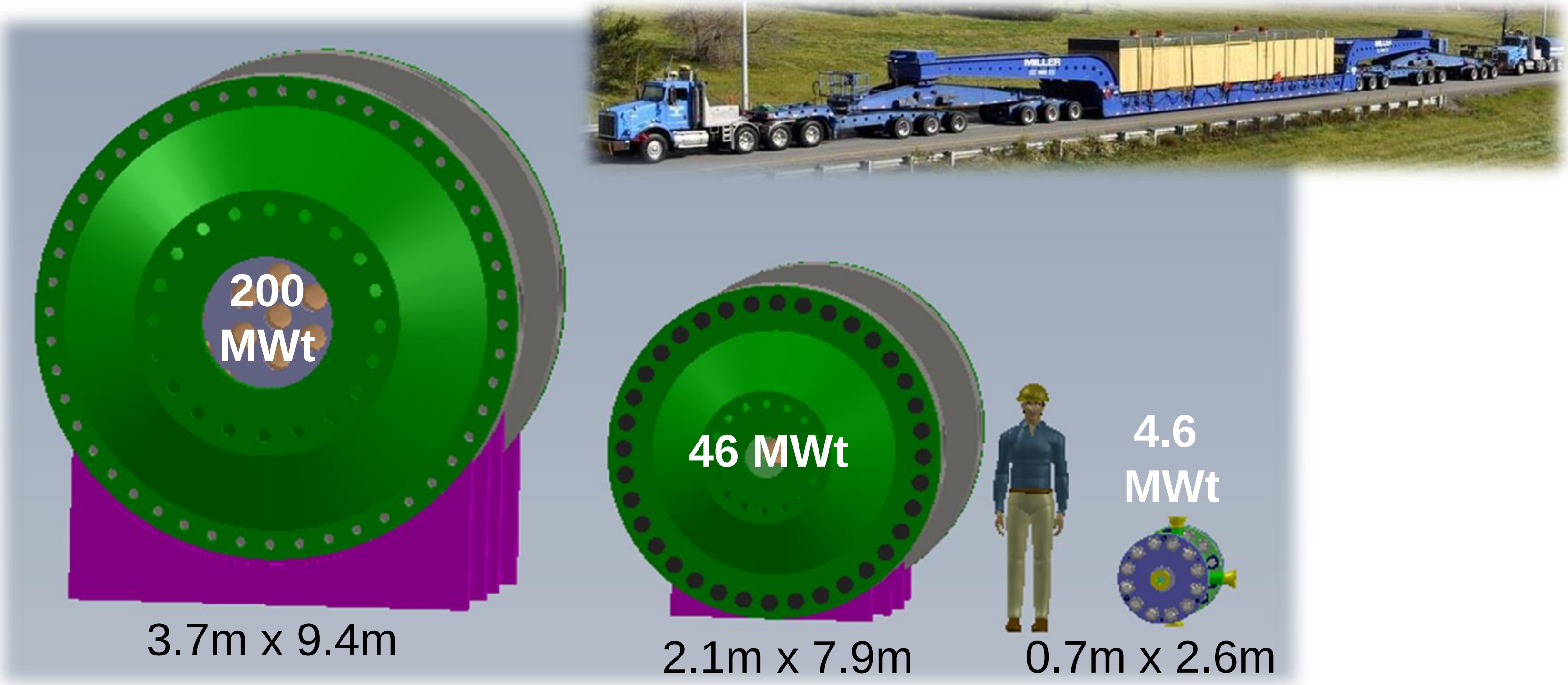
- Laser cutting
- Laser welding
- Water jet cutting
- 3D metals printing
- Electrochemical etching
- Electrochemical machining (ECM)
- Electro discharge machining (EDM)
- EDM wire cutting
- Sheet bending/forming
- Metal plating
- Stamping
- Brazing
- Welding
- Diffusion bonding



46 MWt Microtube Recuperator

Smaller, modular tube bundles are preferred to a single large tube bundle design

- **Factory fabricated**
- **Economies of scale lower costs**
- **Removable tube bundles for maintenance and repair**
- **Each tube bundle has its own floating tube sheet**
- **200 MWt unit meets shipping criteria**



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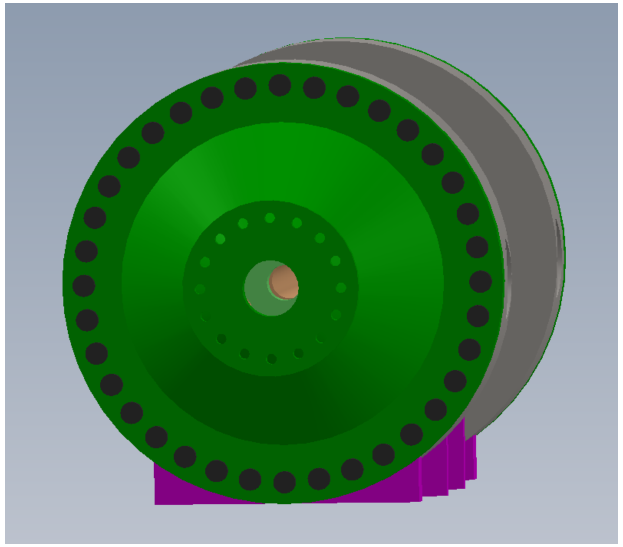
Recuperator Concepts
Engineering Analysis

46 MWt, 280 bar, 610°C, 97% Effectiveness, ΔP < 1.3 bar, <$100/kWt

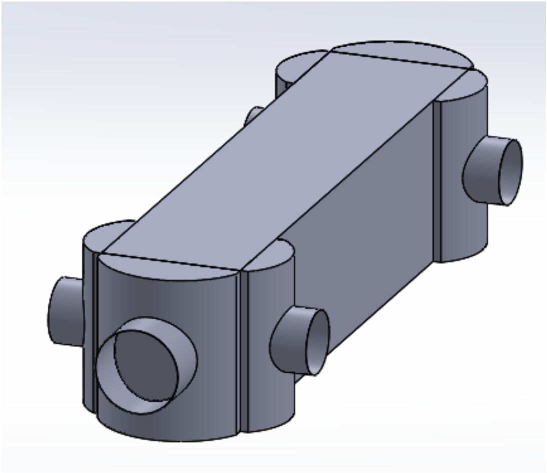
Microtube



$51/kWt

✓

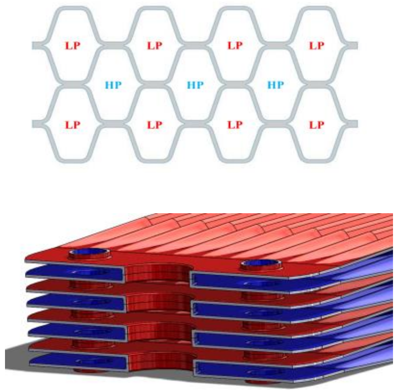
Stacked-Sheet



$47/kWt

✓

Corrugated



> $107-380 /kWt

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Project Update

- Prototype Design & Fabrication
- Prototype Performance Testing

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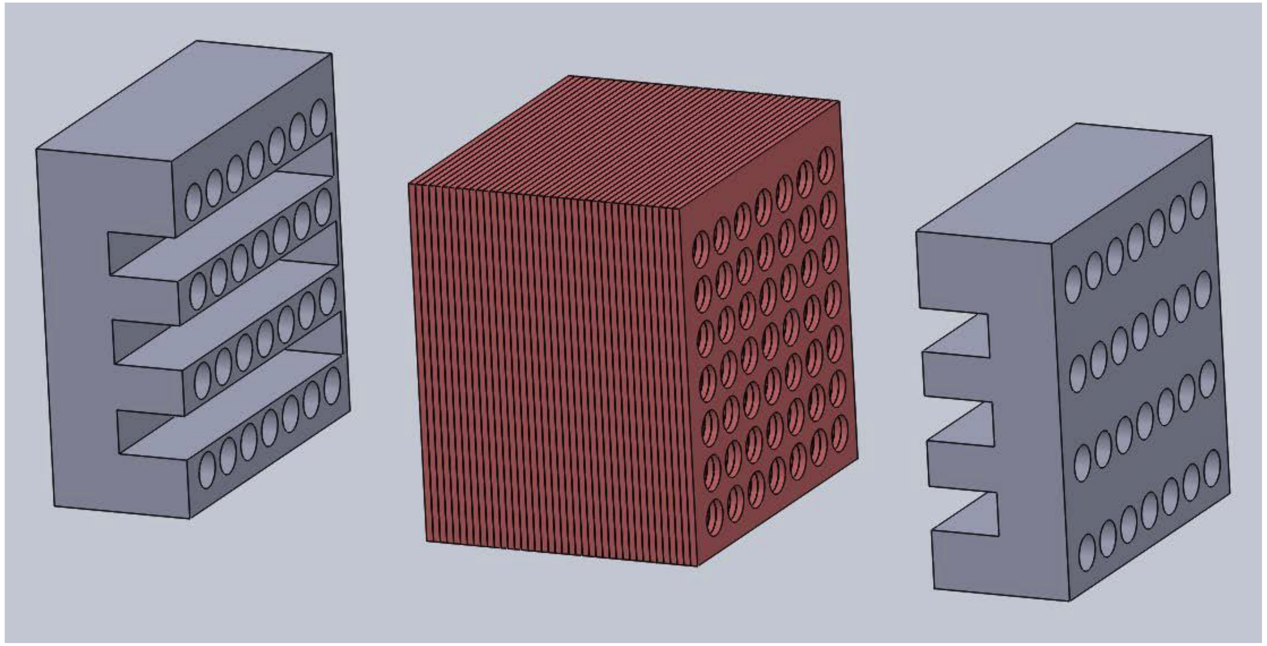
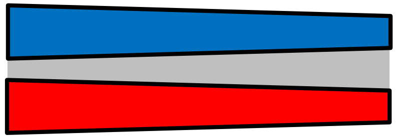
Stacked-sheet Recuperator Concept (SSHX)

Initially discussed as manufacturing method

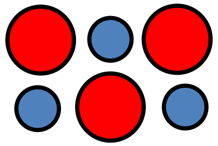


- **Individual sheets have flow channels cut, punched or etched**
- **Individual sheets are stacked and joined (brazed, diffusion bonded)**
- **Manifolds/headers are added to distribute flow (stacked sheets, traditional machining, additive mfg)**

Opportunity to enhance recuperator performance by controlling passage size, shape and surface effects without significantly adding manufacturing costs.



Tapered holes



Variable hole sizes

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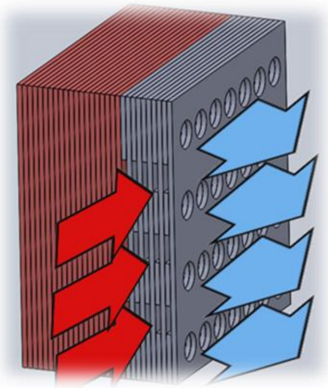
Stacked Sheet Recuperator Concept

Manufacturability effects:

- Surface roughness characteristics in the passages
- Alignment of sheets and manufacturing tolerances
- Diffusion bonding vs. brazing
- QA/QC (e.g. ultrasonics, XCT, optical scanning)

Pressure containment:

- High pressure loading and thermal growth
- Material thickness between passages for containment



CFD
Pressure
Distribution

Manifold/Header Design:

- Ensure uniform flow distribution through the core

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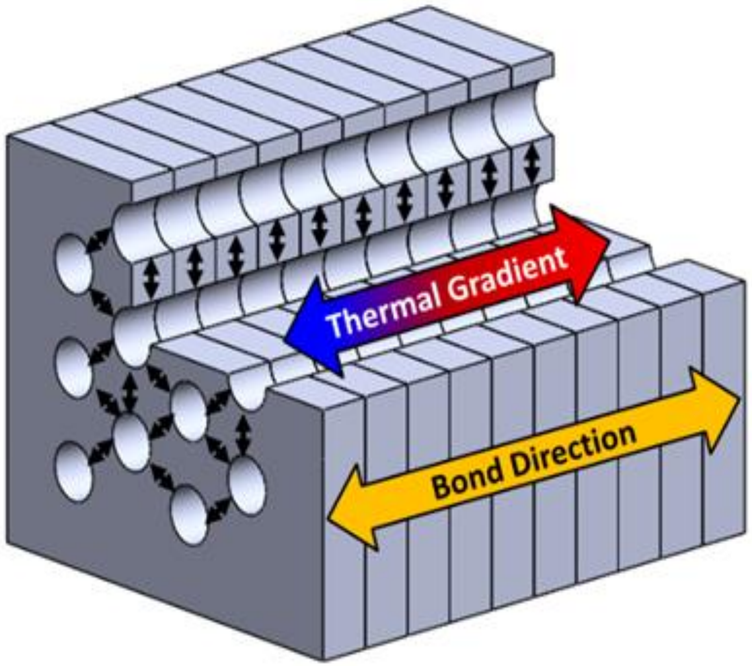
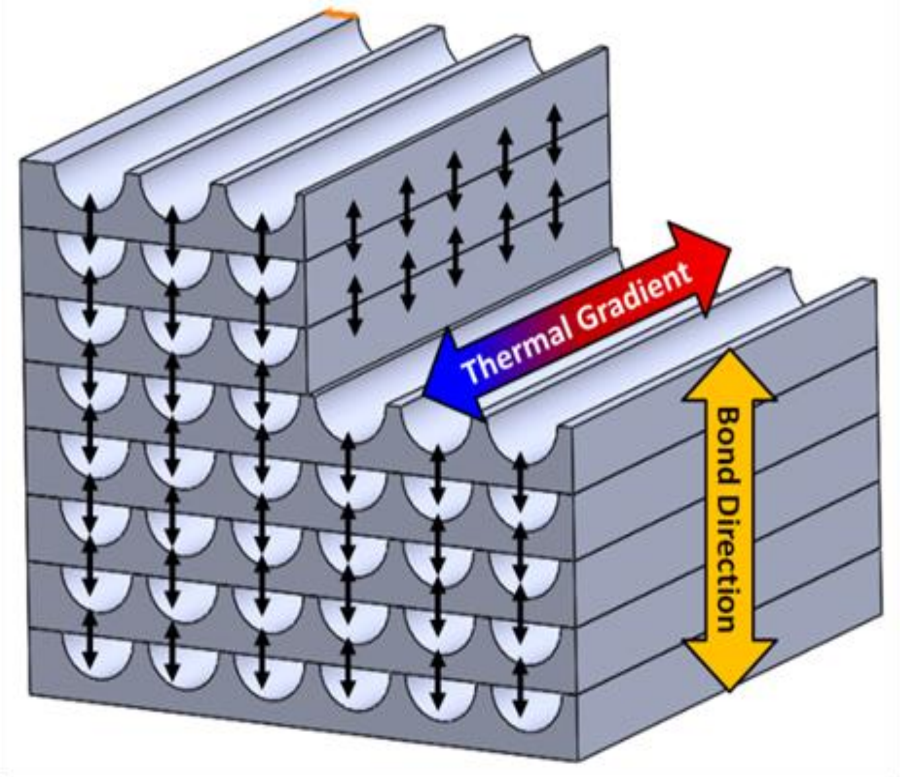
SSHX and Printed-Circuit HX Mechanical & Thermal Stress Analysis





SSHX: ***The bond between sheets is <u>parallel</u> to the mechanical stresses and <u>perpendicular</u> to the thermal gradient stresses***

Improves structural integrity and thermal compliance

Printed-Circuit HX: ***The bond between sheets is <u>perpendicular</u> to the mechanical stresses and <u>parallel</u> to the thermal gradient stresses***

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SSHX Manufacturing Options
Extensive discussions with Vendors

Subtractive vs. Additive Manufacturing

- **Stamp or punch operations (Opacity ~73%)**
- **Laser Drilling**
- **Water Jet Drilling**
- **High Pressure Drilling**
- **Chemical etching**
- **Electrochemical machining**
- **Electro-polishing**
- **Mechanical Grinding**
- **Plate and Sheet Re-rollers**
- **Additive Manufacturing – 3D printing (Opacity ~38%)**

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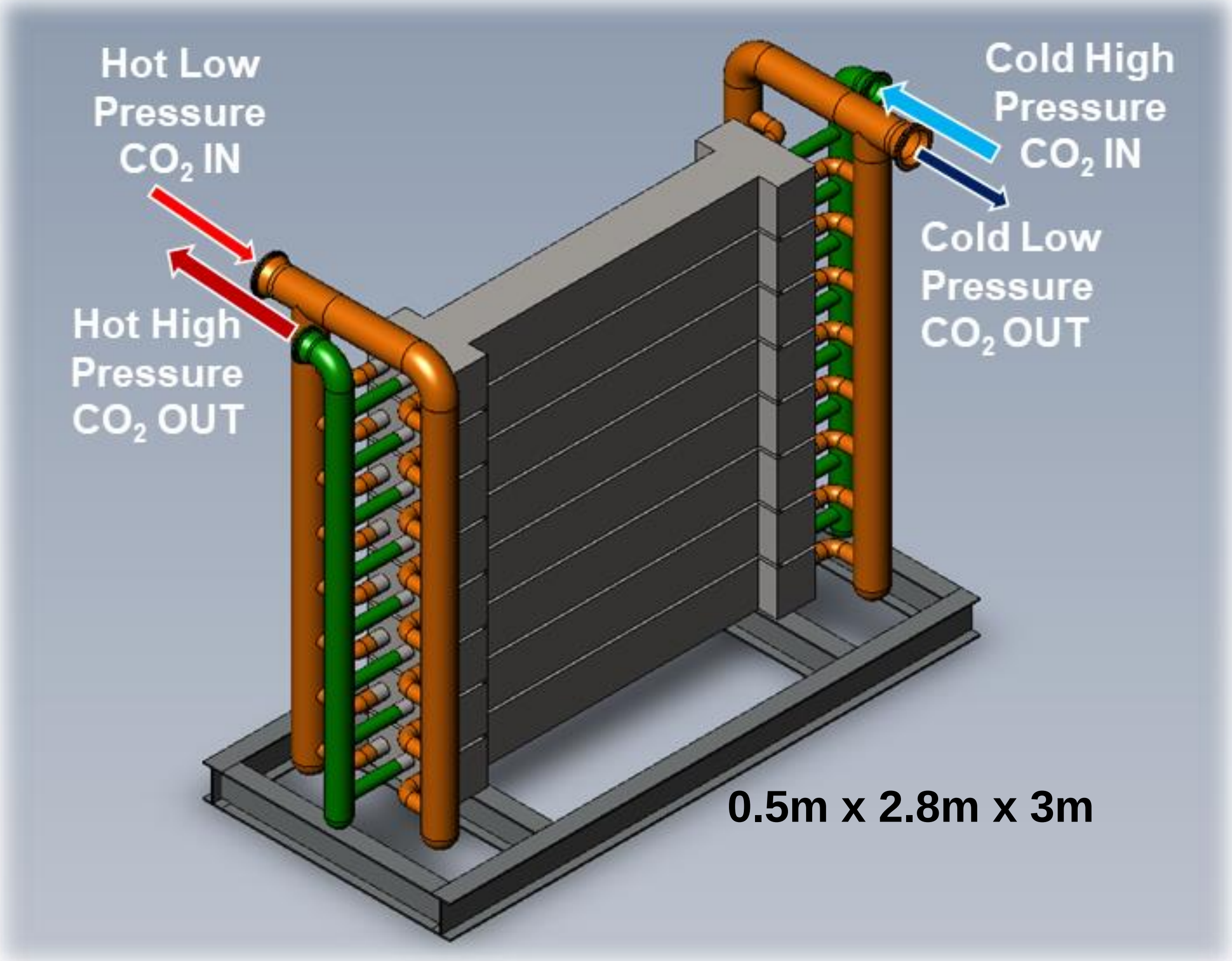
Prototype Recuperators

Criteria	3D-SSHX Prototype	Laser-SSHX Prototype
Manufacturing Method	3D Printed	Laser Cut Sheets
Materials	Inconel 625	Stainless 347H
Channel Pattern	Circle-Star	Circle-Circle
Manifold Design	3D Printed	Laser Cut Sheets
Joining Method	Diffusion Braze	Diffusion Braze
Opacity	~46%	~73%

46 MWt Laser-SSHX Recuperator

Example: Eight stacked Laser-SSHX sub-modules



3D-SSHX 57% volume decrease

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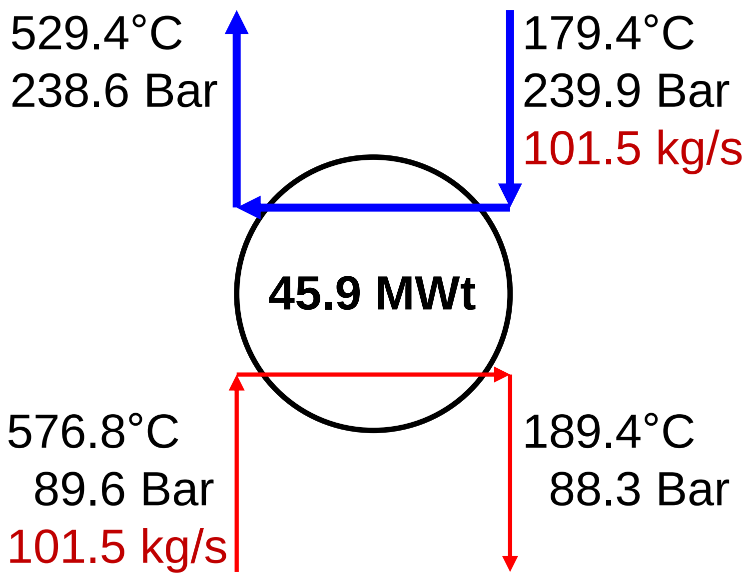
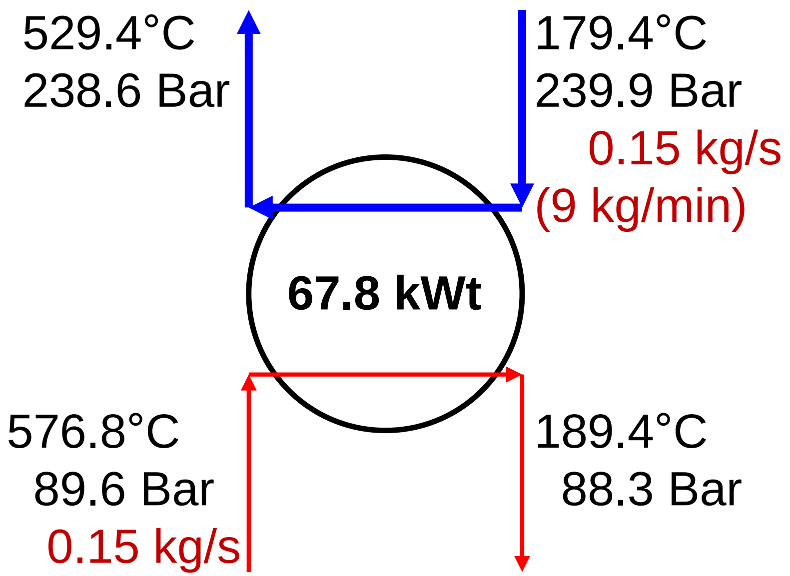
STEP Recuperator Prototype Test Loop

Updated Conditions



Prototype Test Conditions



- **Test thermal performance over a range of operating conditions**
- **Compare actual to predicted performance**
- **Rank prototypes by performance**

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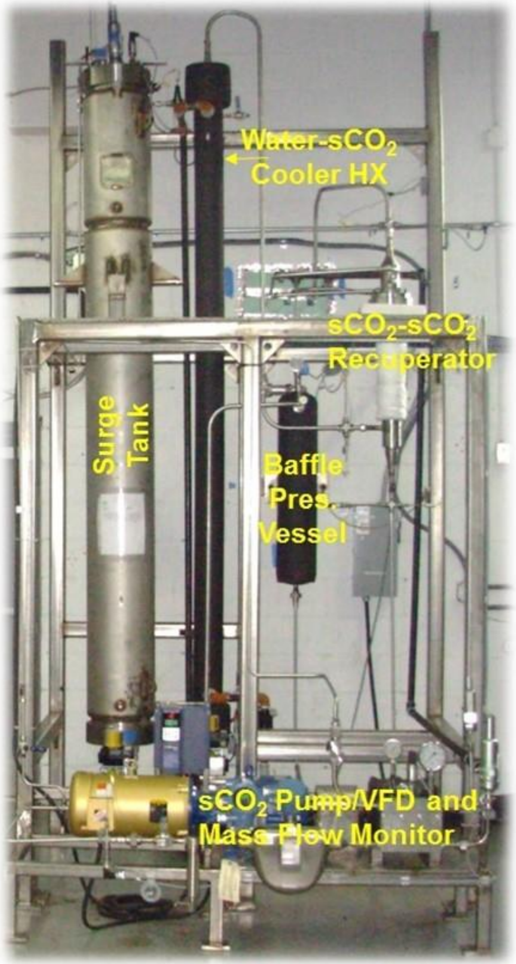
sCO_2 Brayton Power Cycle Heat Exchanger Test Facility

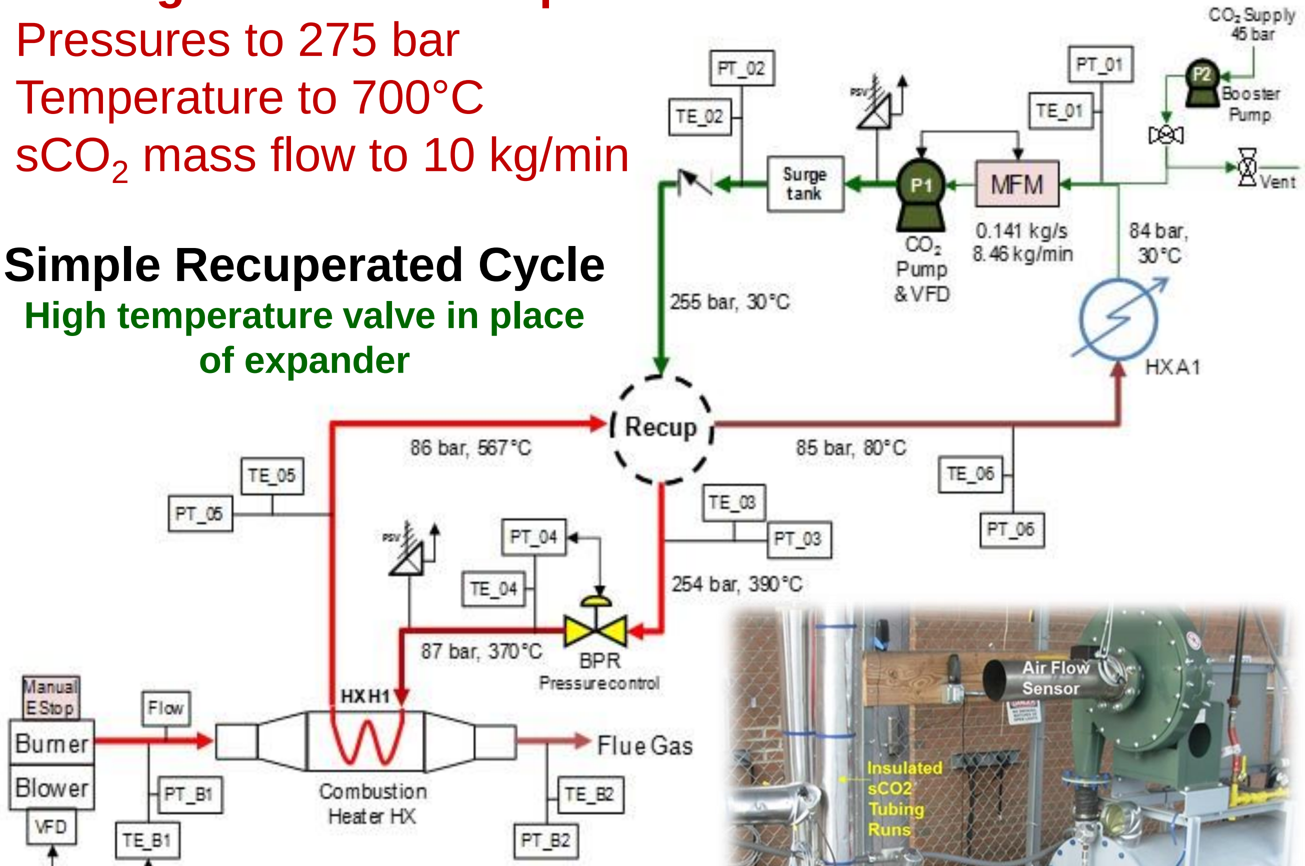


Reconfigurable Test Loop

- Pressures to 275 bar
- Temperature to 700°C
- sCO_2 mass flow to 10 kg/min

Simple Recuperated Cycle

High temperature valve in place of expander



Work supported by US DOE NETL under DE-FE0024012 & DE-FE0025348

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HX Model Heat Transfer Equations

Models selected from established heat transfer and pressure drop equations for the best accuracy compared to testing data

1 CO_2 Side Nusselt Number

Petukhov (1970)

$$Nu_{CO_2} = \frac{\left(\frac{f}{2}\right) \times Re \times Pr}{1.07 + \frac{900}{Re} - \frac{600}{1+10\mathrm{Pr}} + 12.7\left(\frac{f}{2}\right)^{\frac{1}{2}}\left(Pr^{\frac{2}{3}} - 1\right)}$$

2 Air Side Nusselt Number

Martin (2002)

$$Lq = \begin{cases} 0.92Hg \times Pr_{air}(i) \times \left(\frac{\frac{4X_T}{\pi} - 1}{X_L}\right) & X_L \geq 1 \\ 0.92Hg \times Pr_{air}(i) \times \left(\frac{\frac{4X_T X_L}{\pi} - 1}{X_L X_D}\right) & X_L < 1 \end{cases}$$

$$Nu_{air}(i) = 0.404 \times Lq^{\frac{1}{3}}$$

3 CO_2 Side Pressure Drop

Bhatti and Shah (1987)

$$f = 0.00128 + 0.1143Re^{-0.311}$$

$$\Delta p_{co_2} = f \frac{L}{d_o} \frac{\rho \mu^2}{2}$$

4 Air Side Pressure Drop

Zukauskas (1988)

$$\Delta p_{air} = N_r X \left(\frac{\rho {u_m}^2}{2}\right) f$$

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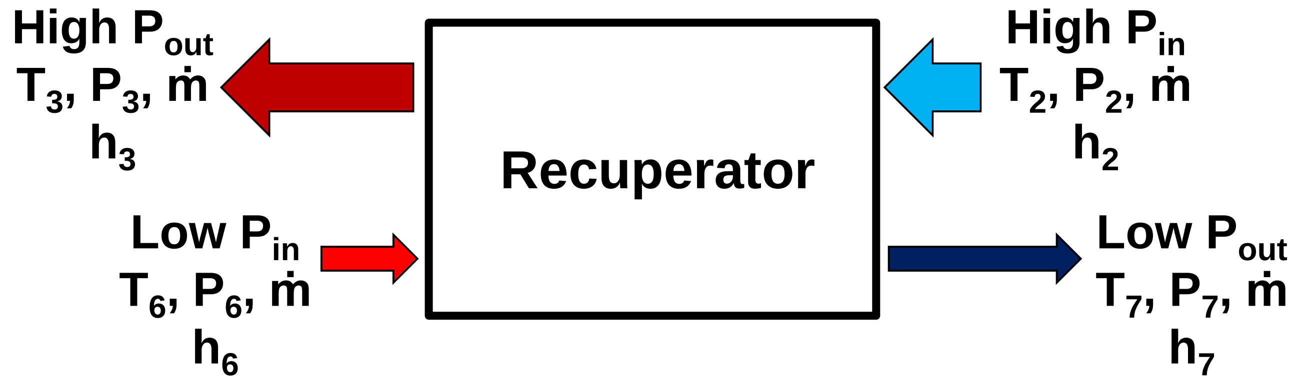
HX Performance Heat Transfer Equations



Effectiveness, $\epsilon = Q_{act} \div Q_{max}$

$$Q_{act} = \text{minimum}(Q_{2\text{-}3}, Q_{6\text{-}7})$$
$$Q_{2\text{-}3} = \dot{m} \times (h_3 - h_2)$$
$$Q_{6\text{-}7} = \dot{m} \times (h_6 - h_7)$$

$$Q_{max} = \text{minimum}(Q_{h\,max}, Q_{c\,max})$$
$$Q_{h\,max} = \dot{m} \times (h_6 - h(T_2, P_7))$$
$$Q_{c\,max} = \dot{m} \times (h(T_6, P_3) - h_2)$$

$AU = Q_{act} \div T_{Ln}$

$$T_{Ln} = (\Delta T_i - \Delta T_{ii}) \div LN\,(\Delta T_i \div \Delta T_{ii})$$
$$\Delta T_i = T_6 - T_3$$
$$\Delta T_{ii} = T_7 - T_2$$

Approach Temperature = $T_7 - T_2$

% Pressure Drop

$$\%\Delta P = (Pin - Pout) / Pin$$

R. K. Shah and D. P. Sekulic, Fundamentals of Heat Exchanger Design, John Wiley & Sons, Inc., 2003

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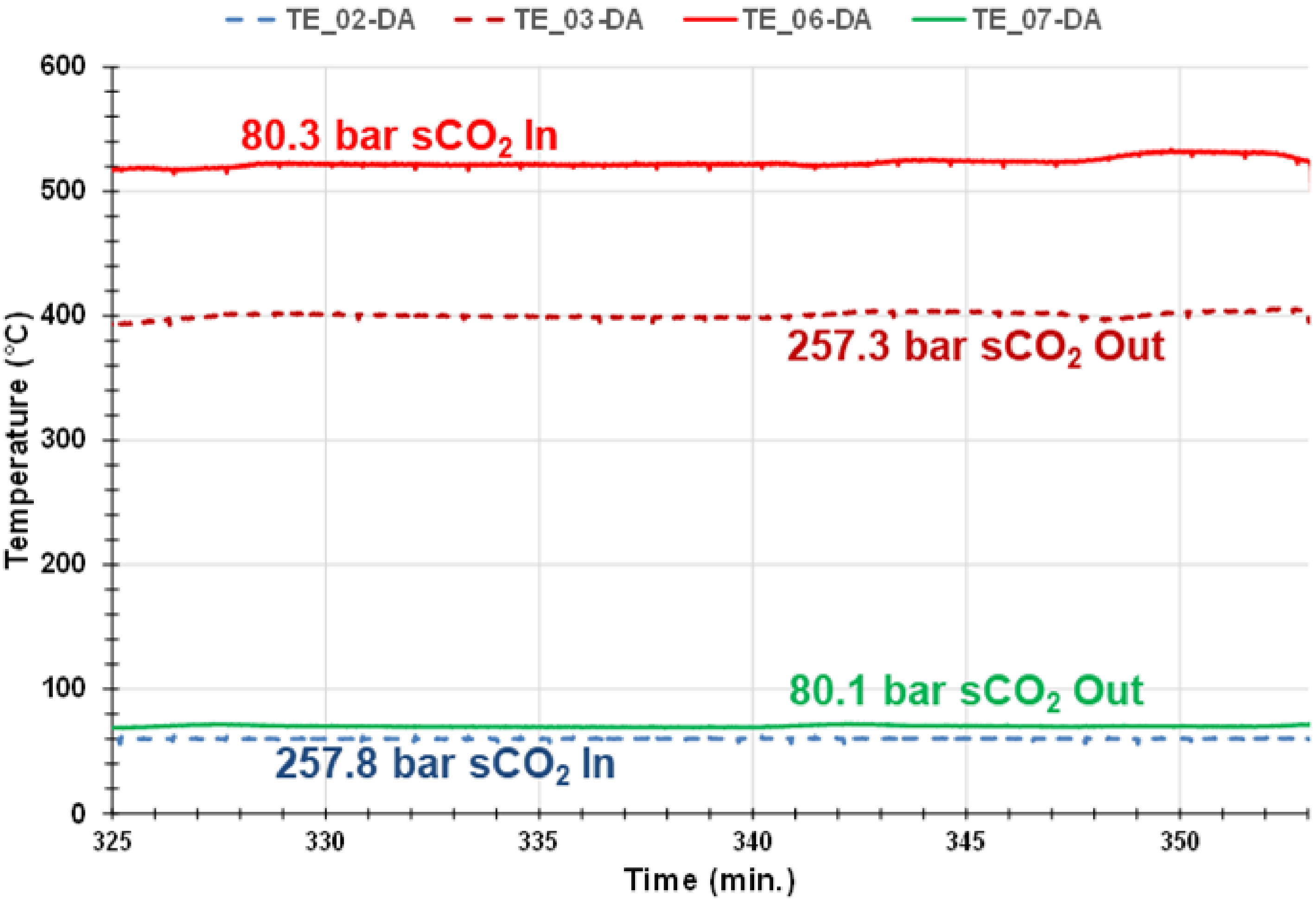
Prototype 3D-SSHX Recuperator

Test Loop Steady State Time vs. Temperature Plot

Mounted in test loop before final insulation installed

Thermal IR image during commissioning



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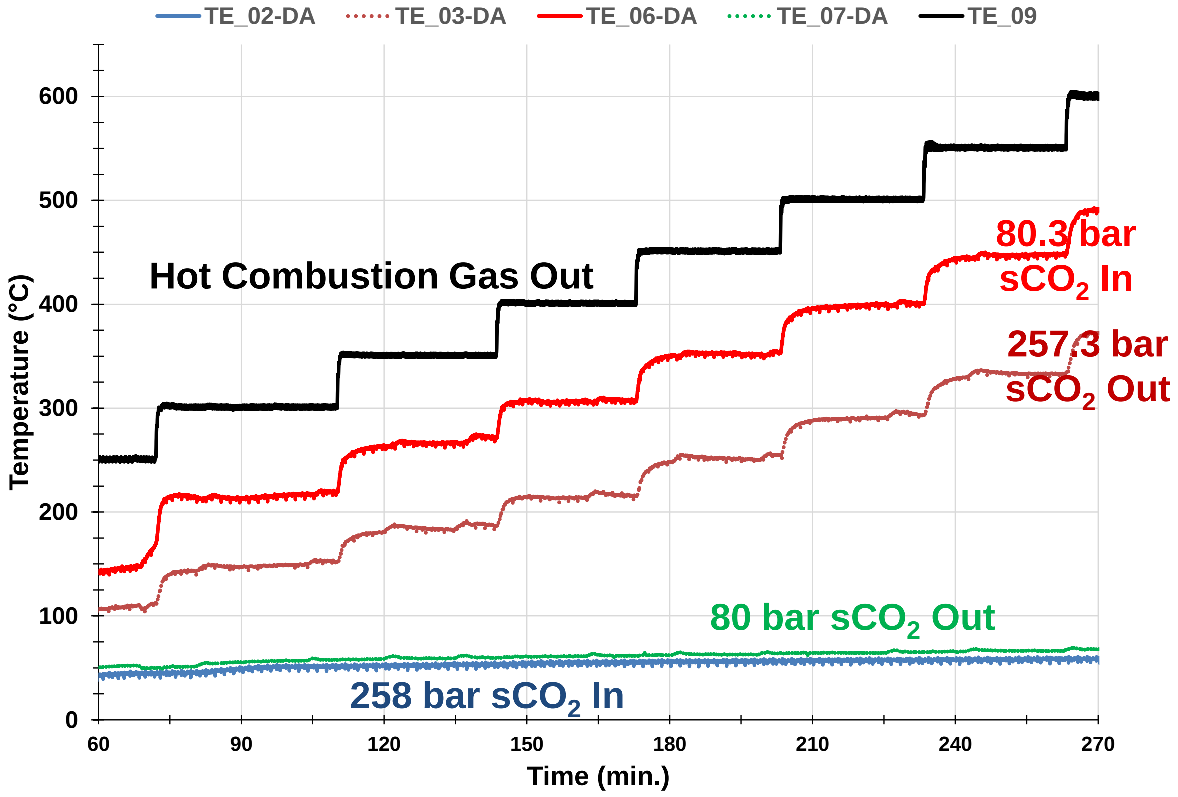
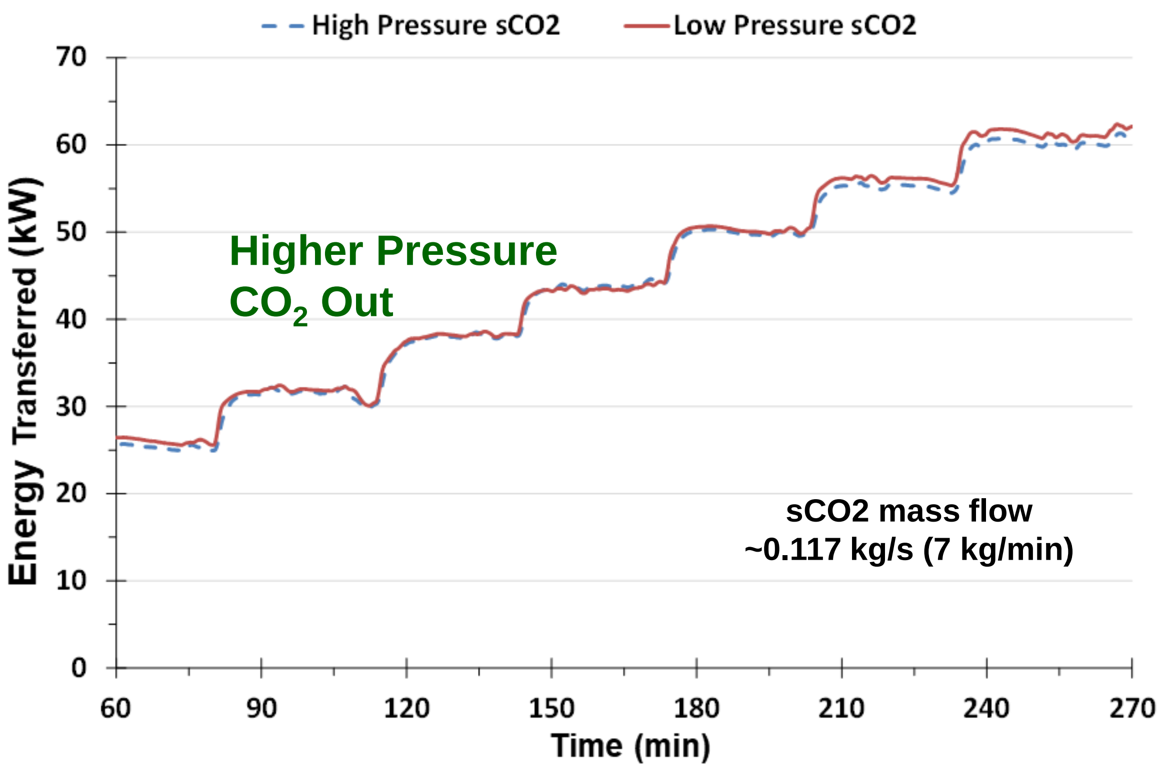
Prototype 3D-SSHX Recuperator
Test Loop Steady State &Energy Balance Plots

Time vs. Temperature Plot



Energy Balance Plot



Good Energy Balance, < 2% error

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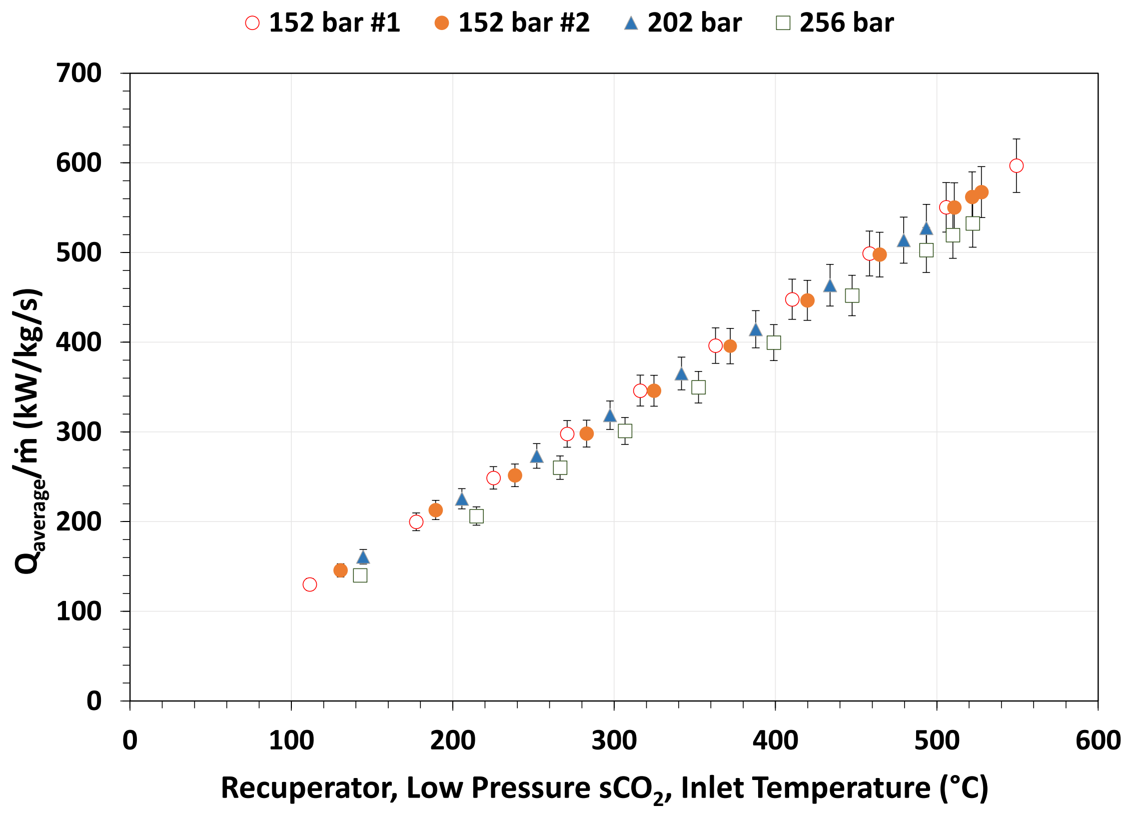
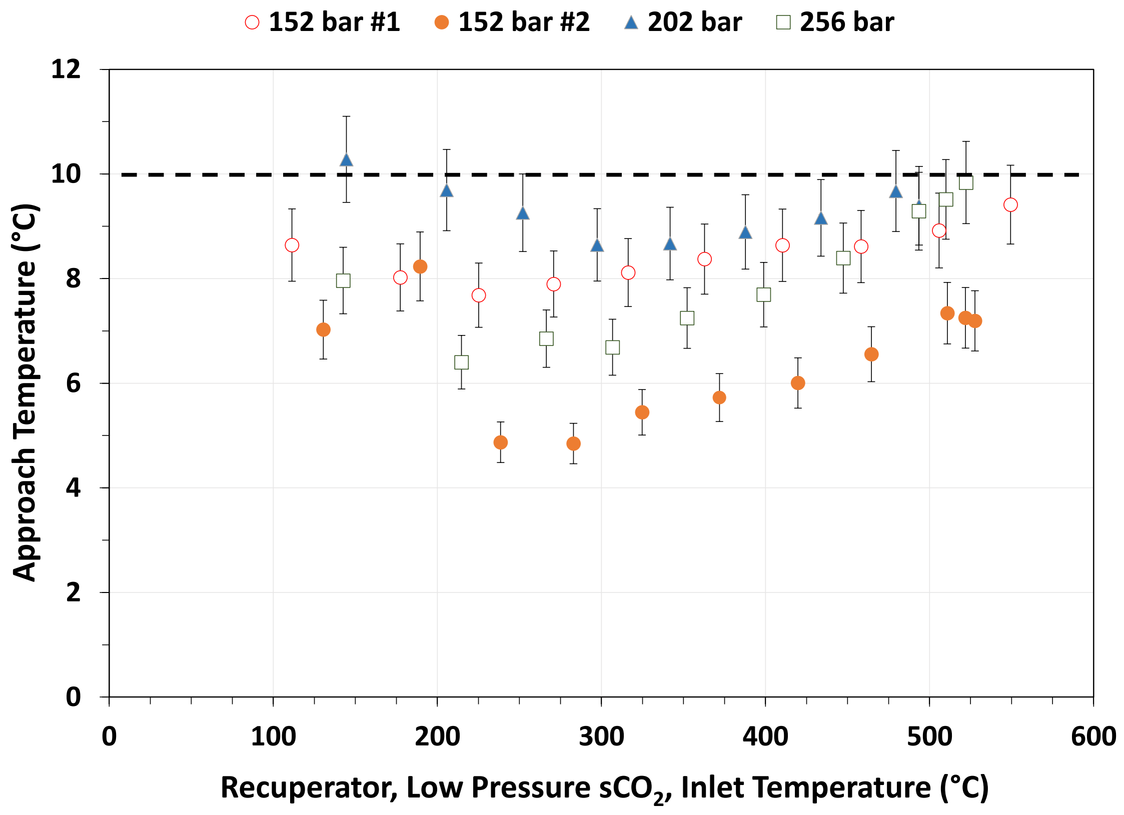
Prototype 3D-SSHX Recuperator
Energy Transfer & Approach Temperature Plots

Meets design specifications

Energy transfer plot



Approach temperature plot



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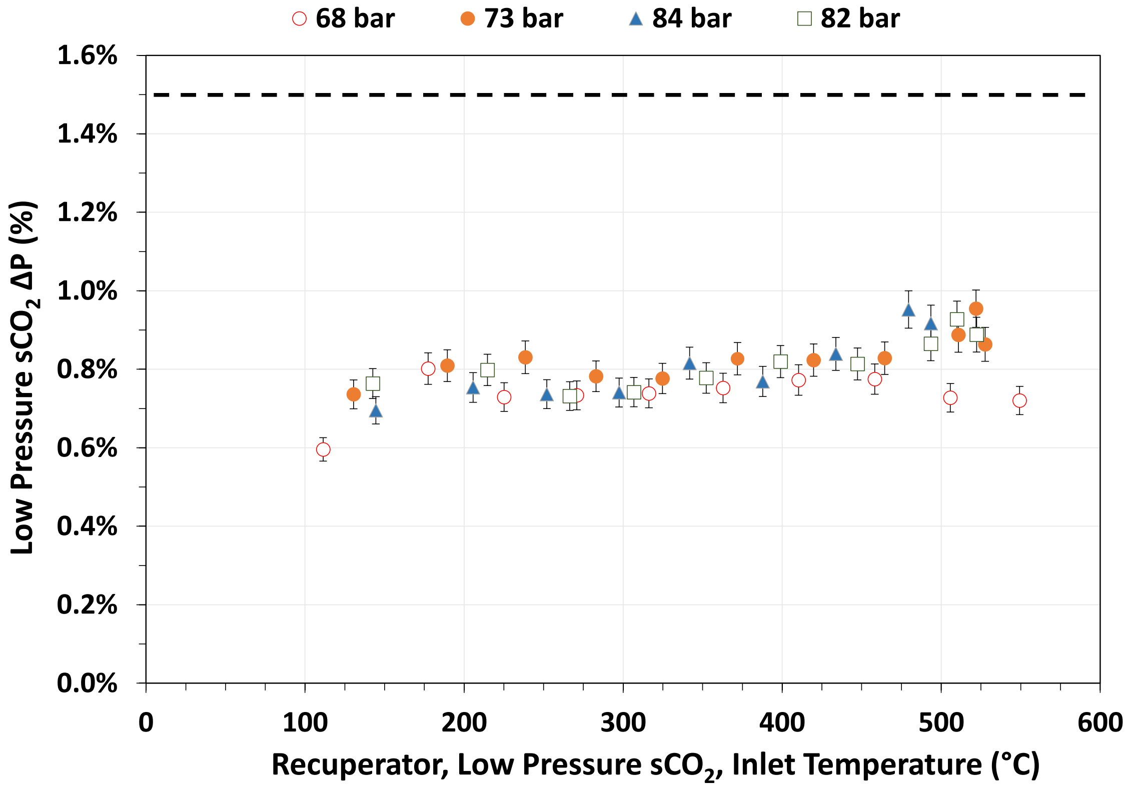
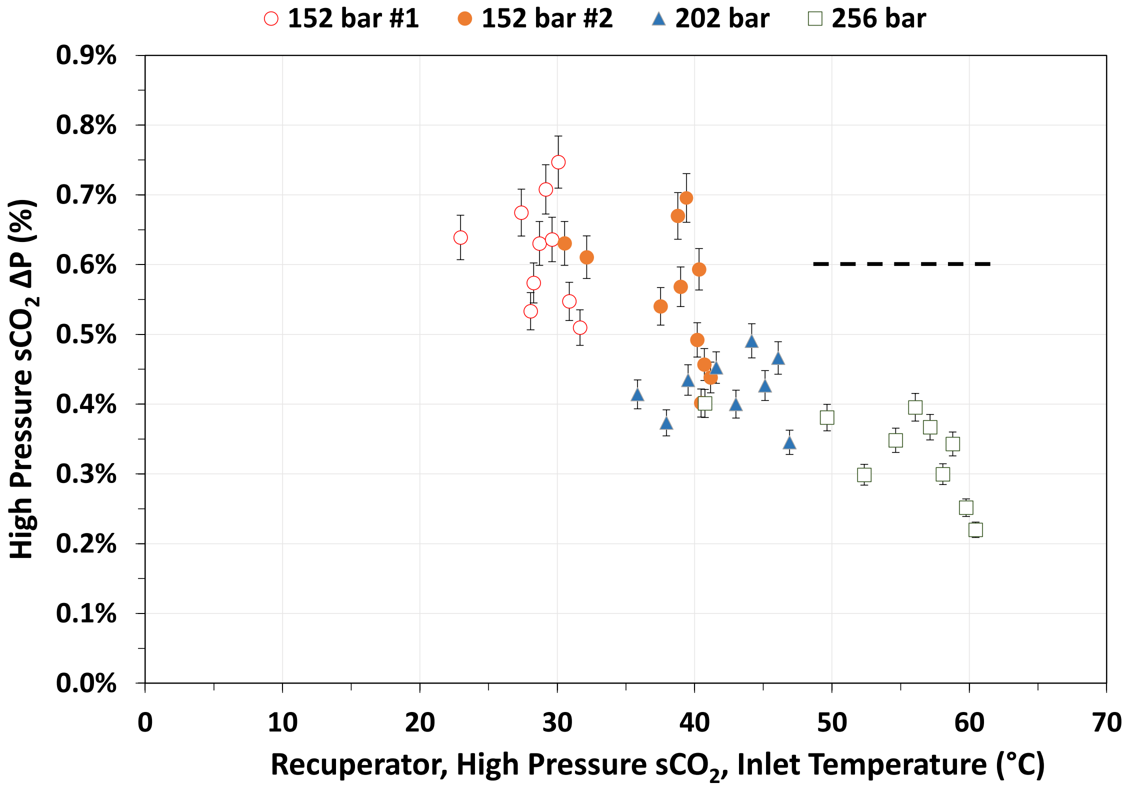
Prototype 3D-SSHX Recuperator Pressure Drop Plots

Meets design specifications

Low Pressure sCO_2 ΔP



High Pressure sCO_2 ΔP



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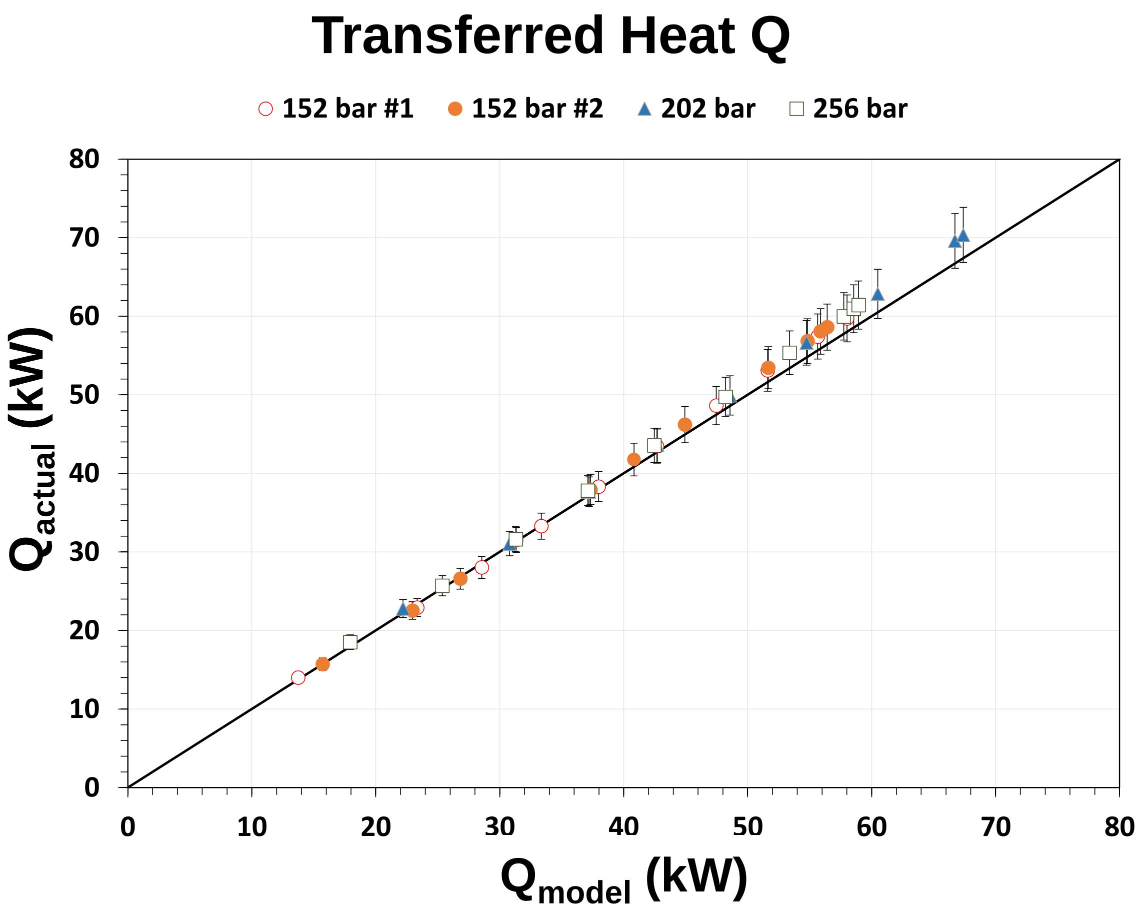
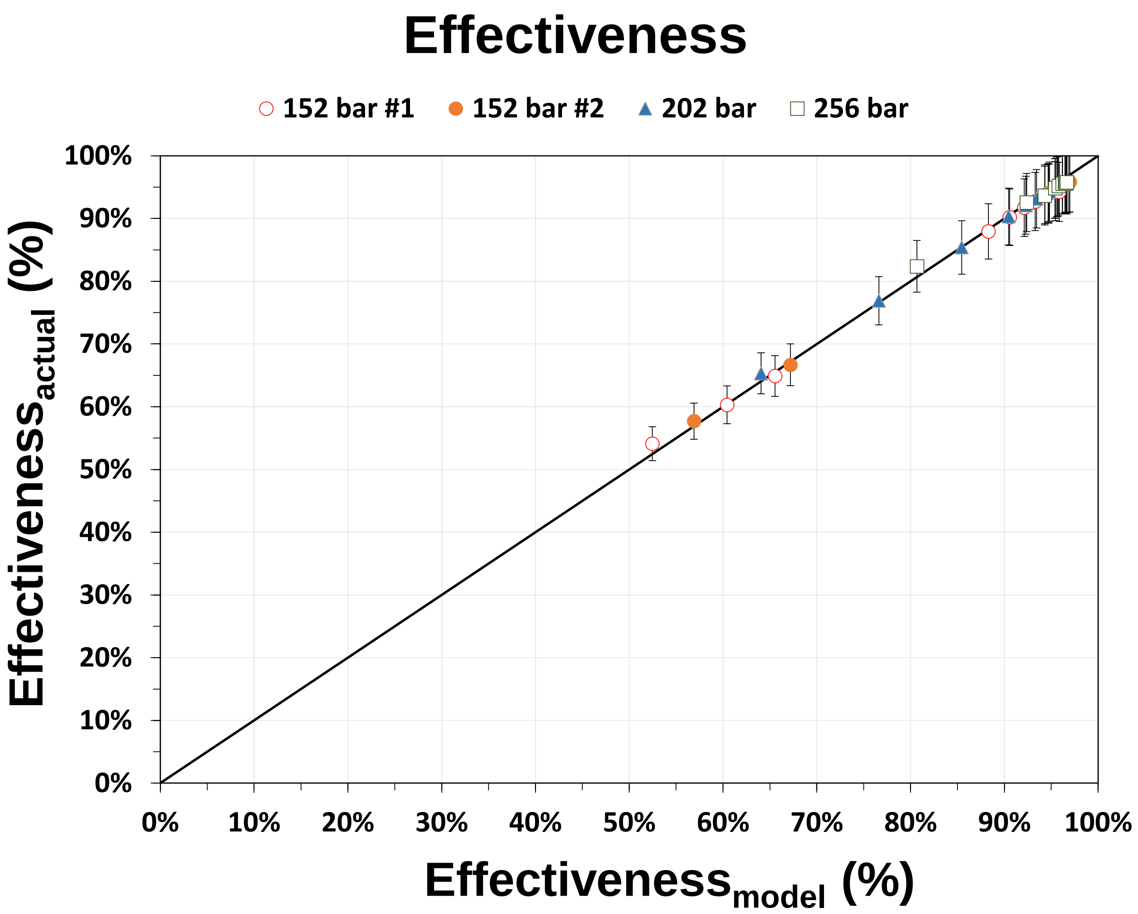
Data confirms 3D-SSHX Recuperator Performance





Good correlation between Design & Actual HX Performance Data

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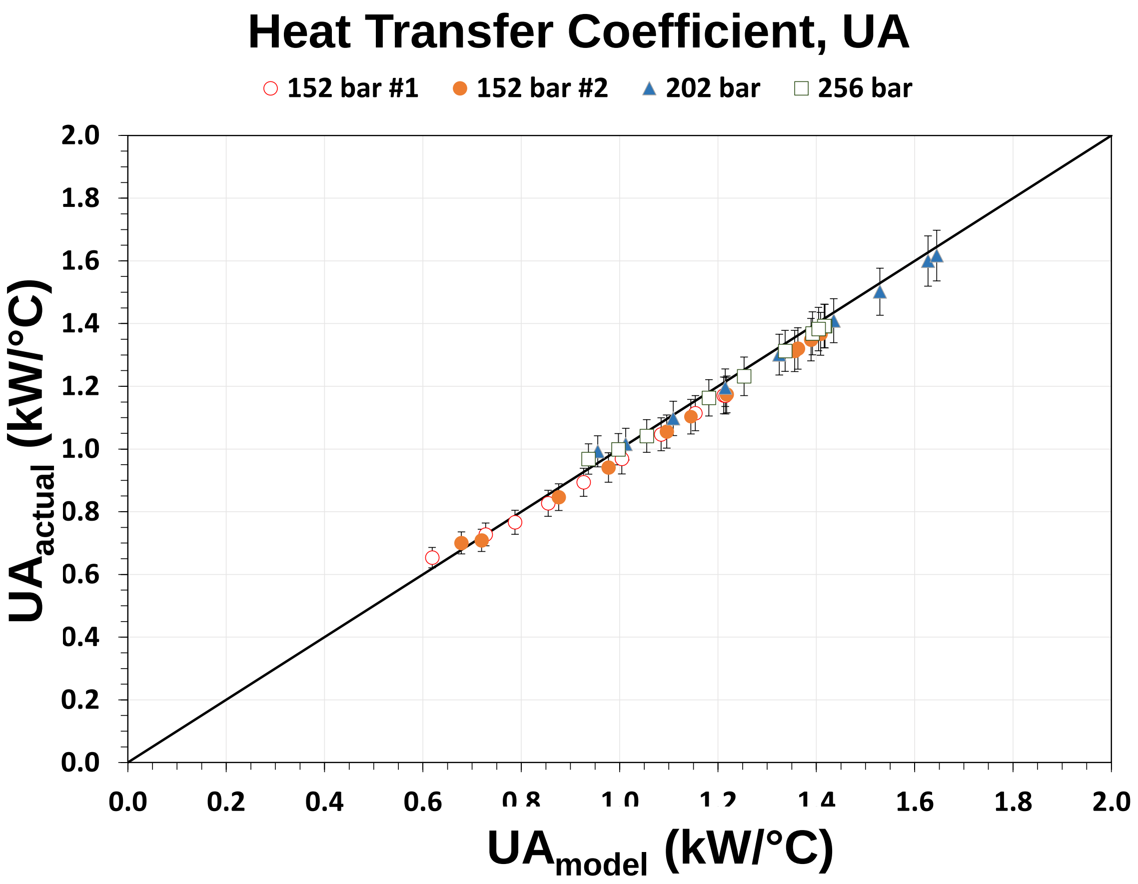
Data confirms 3D-SSHX Recuperator Performance



Criteria	Updated - 8/16/16	3D-SSHX Prototype
Thermal Capacity	**45.9 MWt**	✓
Thermal Effectiveness	**97%**	✓
Pressure Loss	ΔP_h < 1.5% (1.3 bar)	✓
	ΔP_c < 0.6% (1.3 bar)	✓
Temperature Limit	**577°C**	✓
Differential Pressure	152 bar	✓
Life	30,000 hr	TBD
Cost	< $100 / kWt	✓
Package Dimensions	8.8 x 3.6 x 2.6 m	✓

Meets or exceeds program requirements

Summary

- Stacked Sheet and Microtube 46 MWt Recuperator Concepts meet STEP Performance and Cost Criteria and can be scaled to industrial thermal capacity requirements
  - Stacked-Sheet Concept has advantages of lower cost, smaller package size, and potential for future enhancements
  - Microtube Concept has advantages of using a floating tube sheet to accommodate thermal stresses, and a removable tube bundle that accommodates cleaning, maintenance and repair

- Prototype recuperators have been designed and fabricated
  - 3D-SSHX
  - Laser-SSHX

- sCO_2 Heat Exchanger Test Loop has been successfully operated
  - 3D-SSHX prototype recuperator design meets or exceeds HX performance requirements
  - Laser-SSHX prototype testing is scheduled for this quarter.

Thank you for your kind attention

Questions?

Work supported by US DOE under DE-FE0026273
Richard Dennis, Advanced Turbines Technology Manager
Seth Lawson, Program Officer, Advanced Energy Systems Division