2016 University Turbine Systems Research Project Review Meeting

Blacksburg, Virginia
November 2, 2016

# Development of Modular, Low-Cost, High-Temperature Recuperators for the $sCO_2$ Power Cycles

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Thar Energy

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DE-FE0026273

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# Outline

- Introduction to Thar Energy
- Project Overview
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  - Preliminary Engineering Analysis
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  - Preliminary Engineering Findings
  - Prototype Design, Fabrication & Testing
  - Closing Summary

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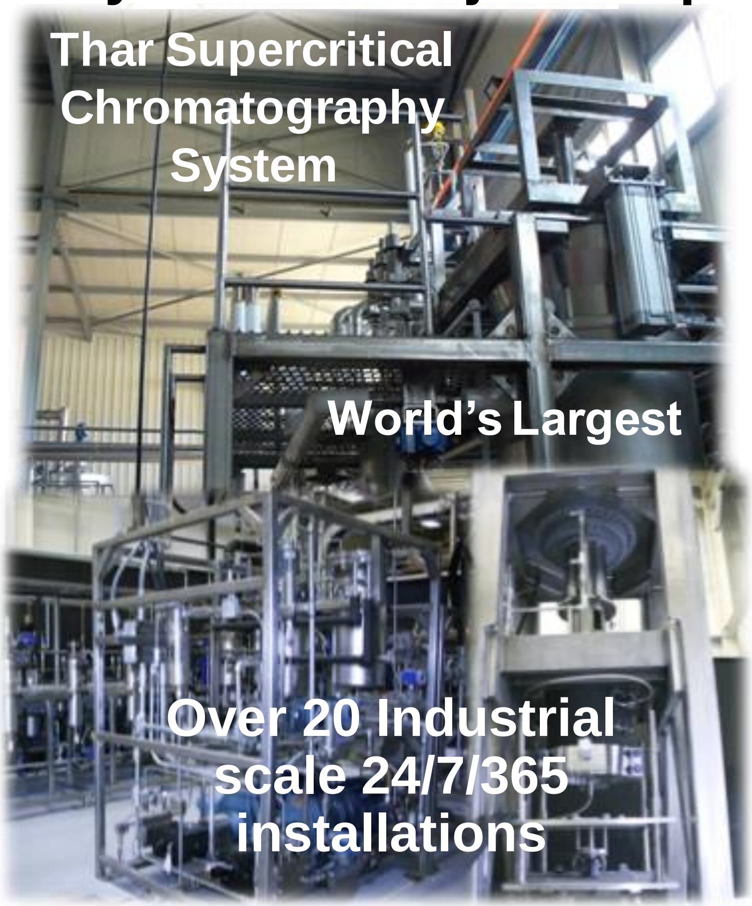
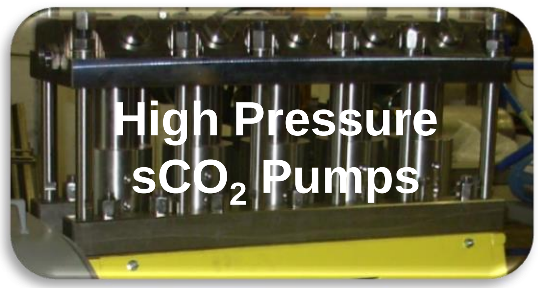
# The Thar Brand - Over 25 years of Innovation with "Green" Supercritical Fluid Technologies

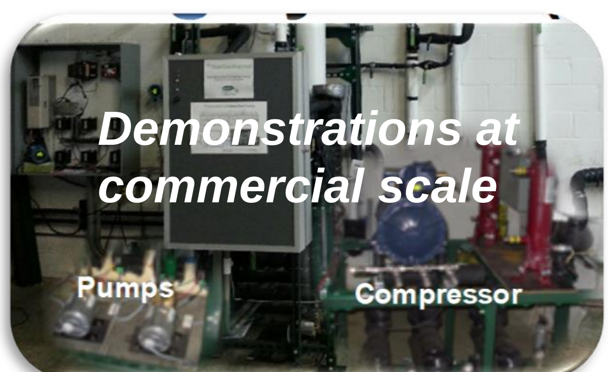
## Design and commercialization of supercritical systems & major components




**Over 5,000 scientific instruments installed**

**Direct Exchange, R744 ($CO_2$) Geothermal Heating & Cooling**

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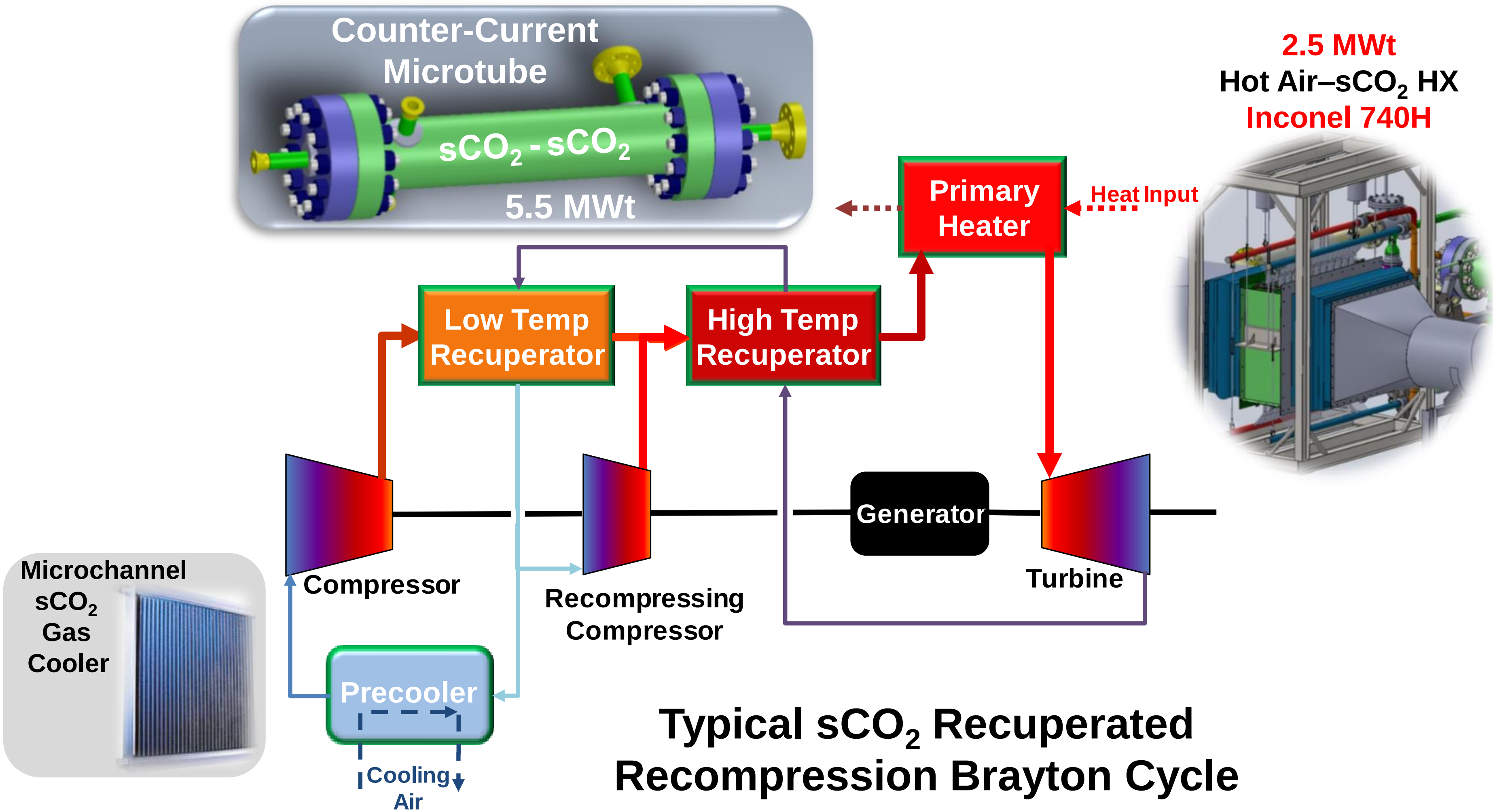
## Heat Exchangers are key to improving $sCO_2$ power cycle efficiency and costs

## Thar Energy $sCO_2$ Recuperators, Primary Heater HXs & Gas Cooler HXs




**Typical $sCO_2$ Recuperated Recompression Brayton Cycle**

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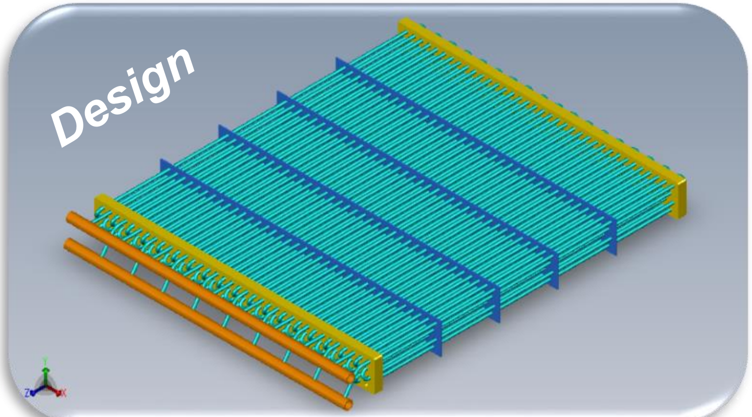
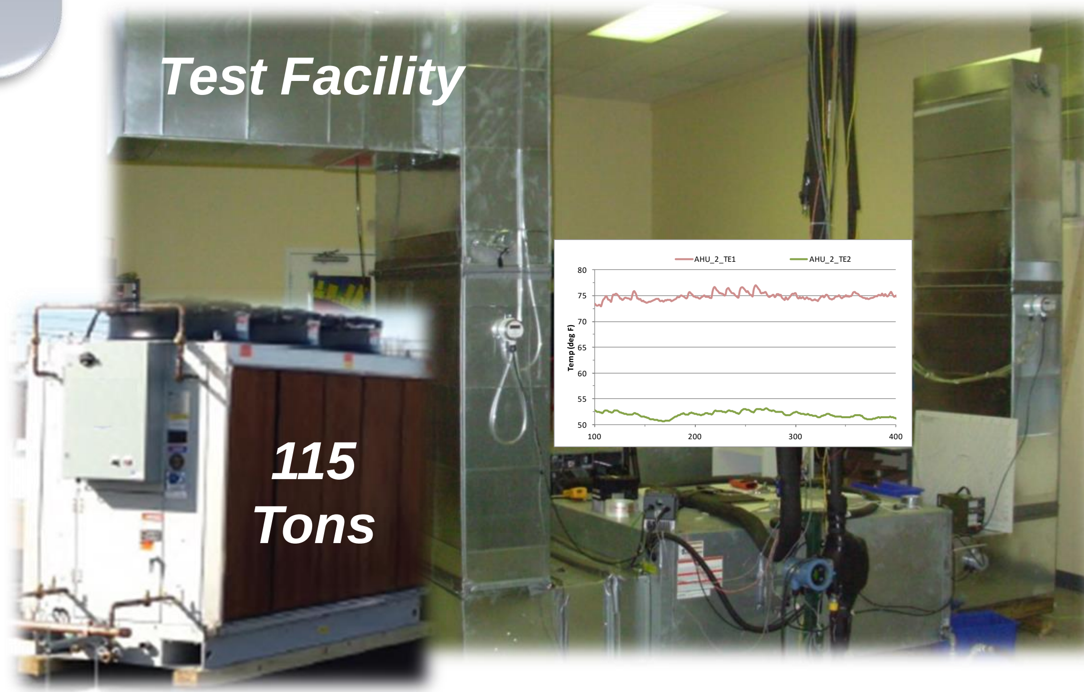
# $sCO_2$ Gas Cooler HXs
# 35-500 kW




**_$CO_2$-Air Approach Temperature as Low as 2°C_**



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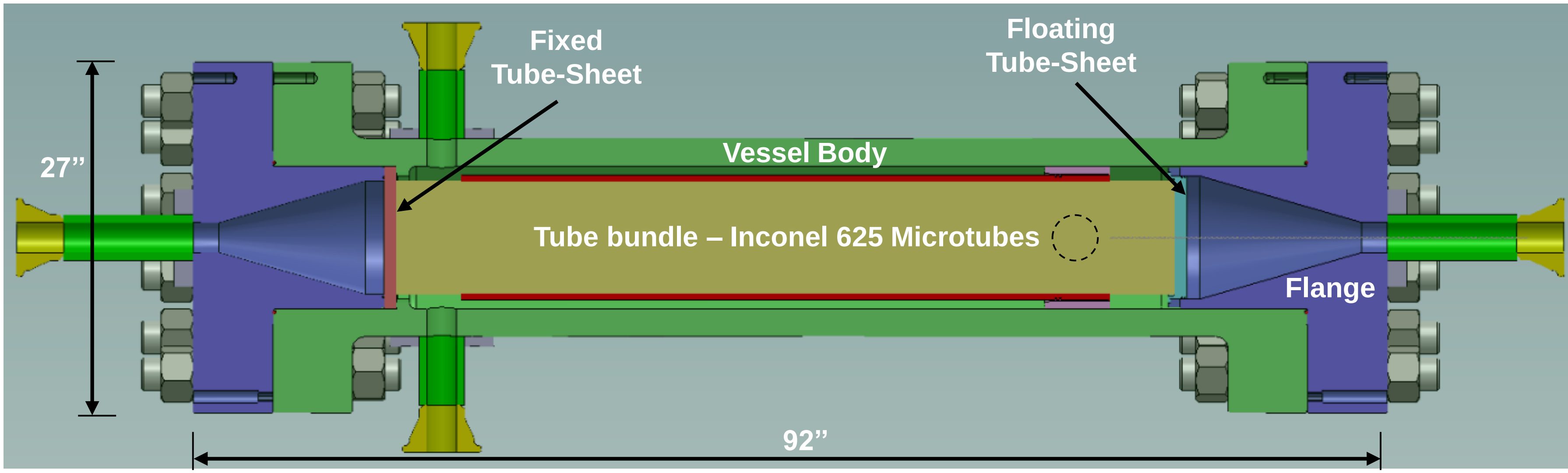
# $sCO_2$ Counter-current Microtube Recuperator




**Flanged Pressure Vessel similar to Shell & Tube:**

- **Floating Head Design**
- **Horizontal Separators vs. Vertical Baffles**
- **Replaceable Tube Bundle**
- **Design per ASME Sec VIII, Div 1**
- **Design Conditions: 575°C @ 280 bar (1053°F @ 4116 psi)**

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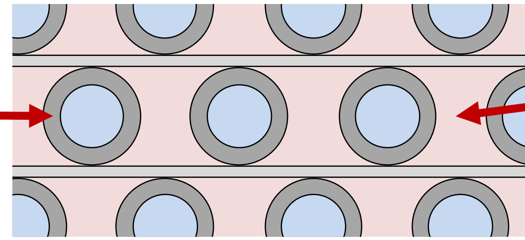
# $sCO_2$ 5.5 MWt Recuperator Tube Bundle

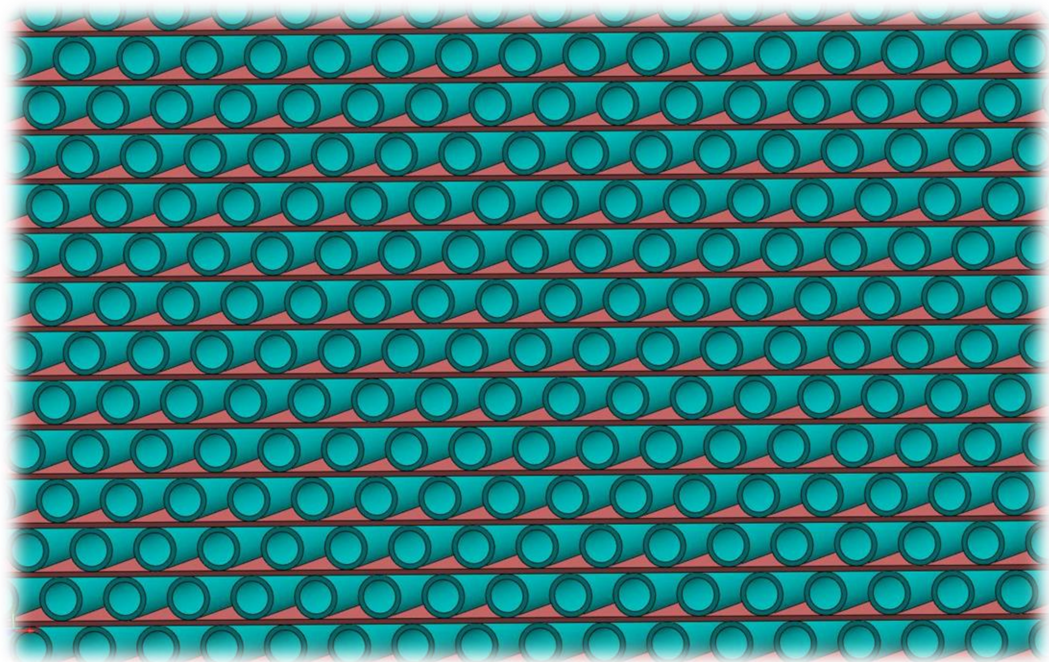
Microtubes
High Pressure **$sCO_2$**



Annular Space
Low Pressure **$sCO_2$**

**> 20,000 microtubes**

**Tube Bundle**
**4,500 $m^2/m^3$**



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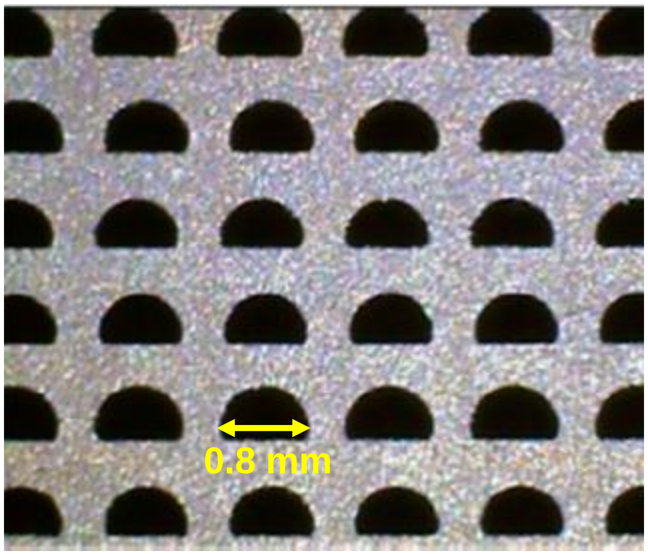
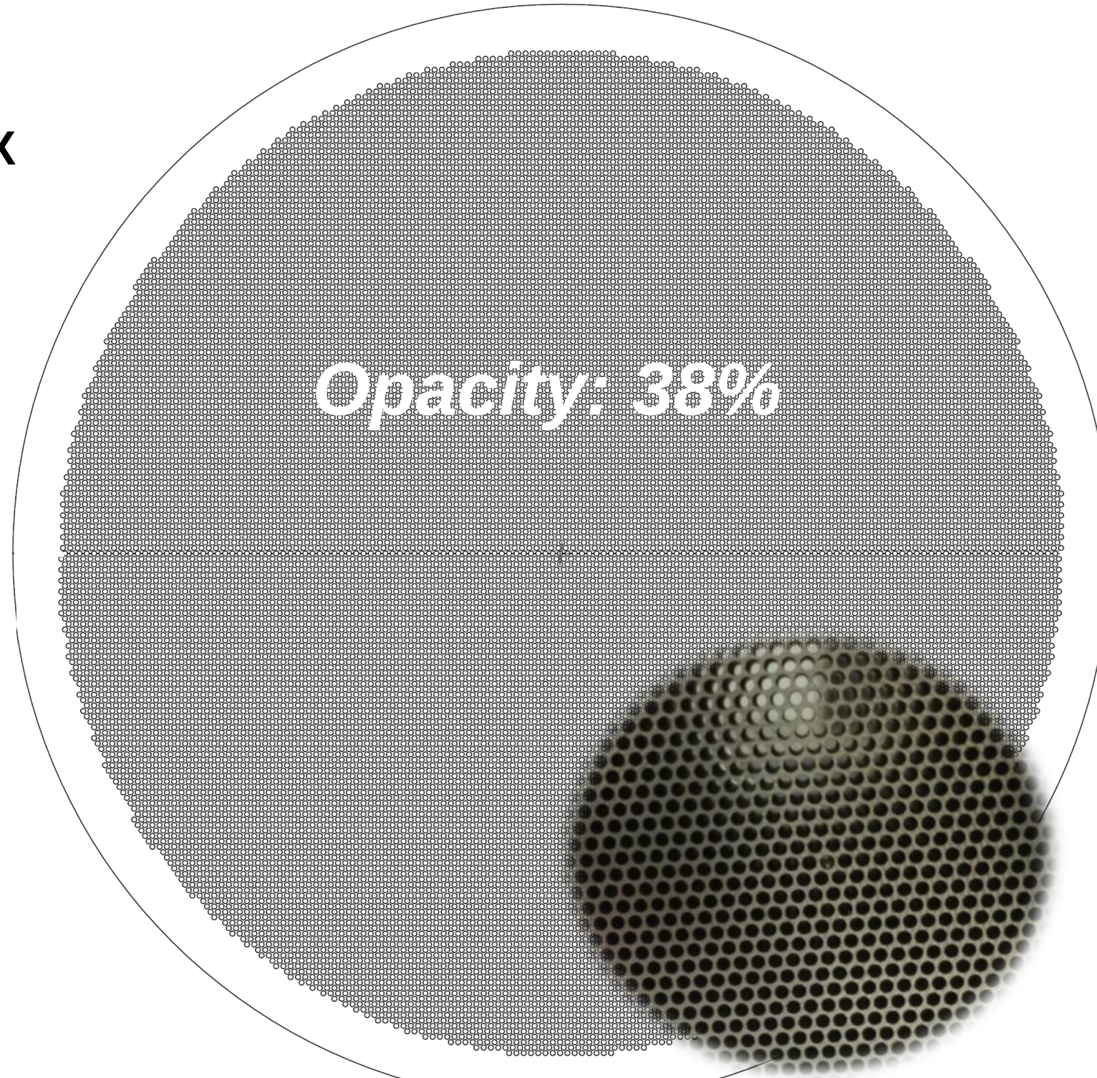
# Recuperator Tube Bundle Cross Section
## 9” diameter, over 20,000 microtubes

### Microchannel Printed Circuit HX



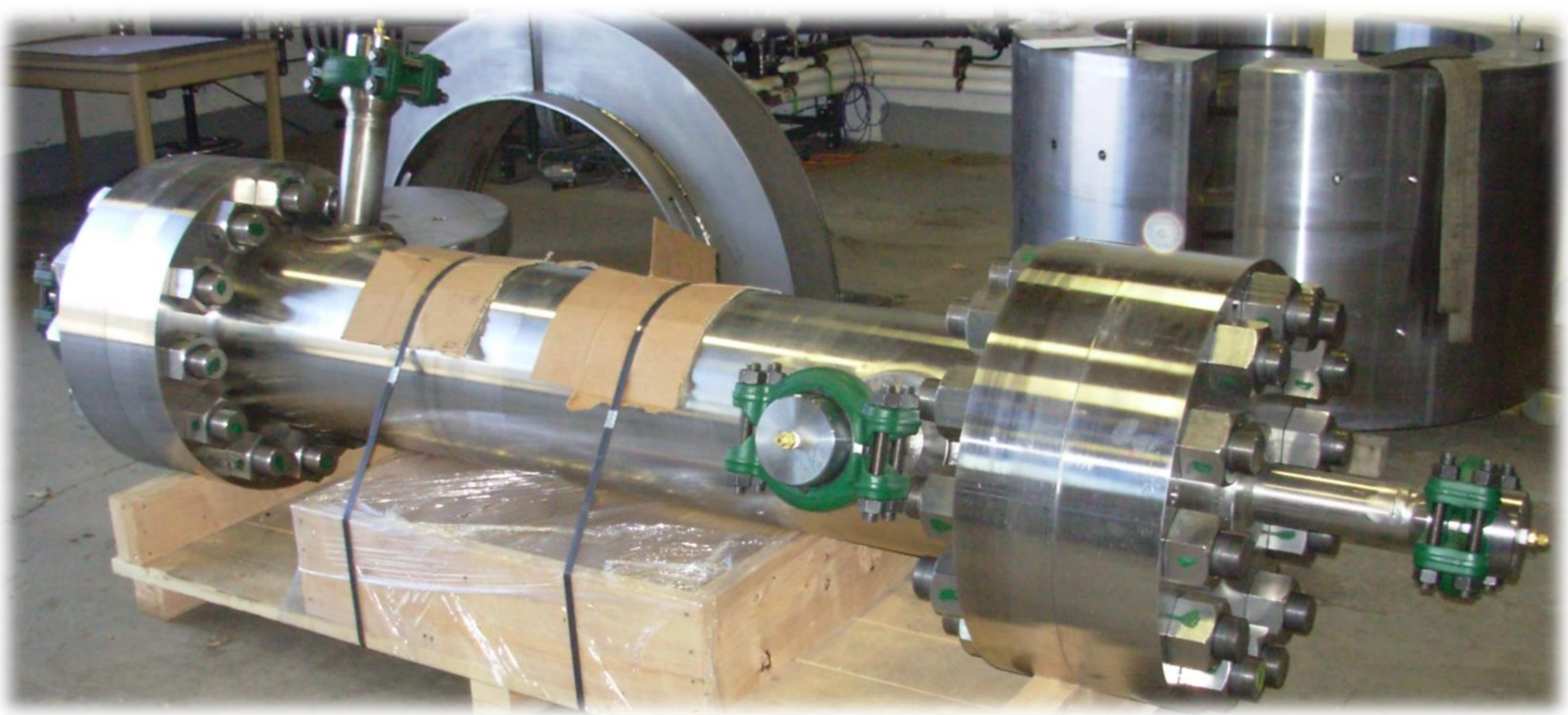

*Entropy* ***2015, 17, 3438-3457; doi:10.3390/e17053438***

**Opacity: 74%**



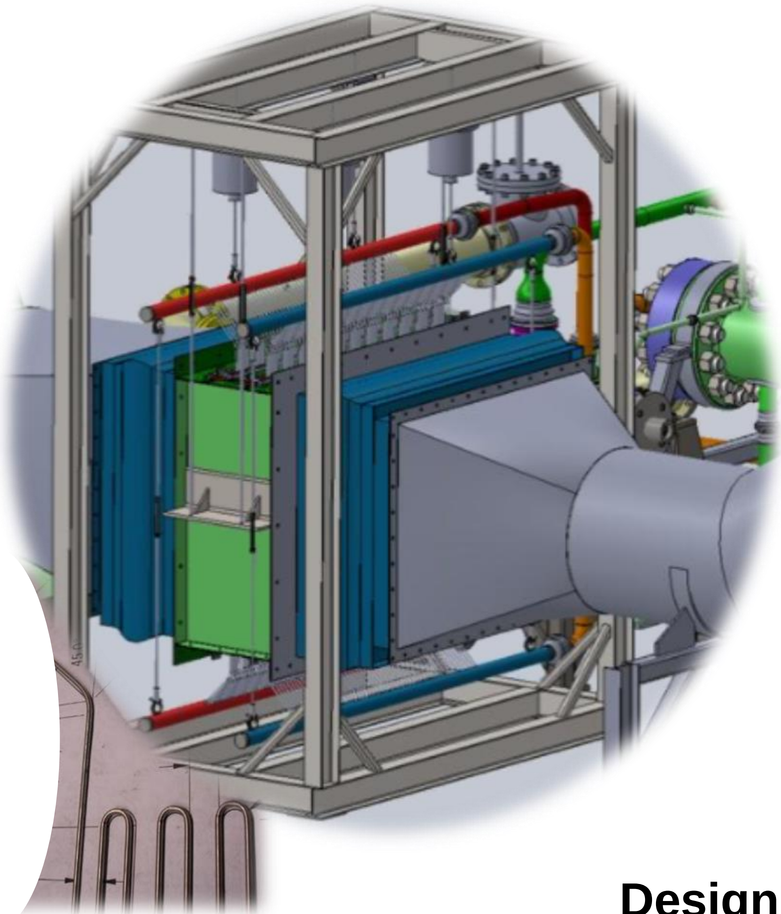
# 1st Generation Recuperator Pressure Vessel

## ASME Stamped - Design Conditions: 575°C @ 280 bar (1053°F @ 4116 psi)



# Sunshot Heater HX Design – 2.5 MW

## 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

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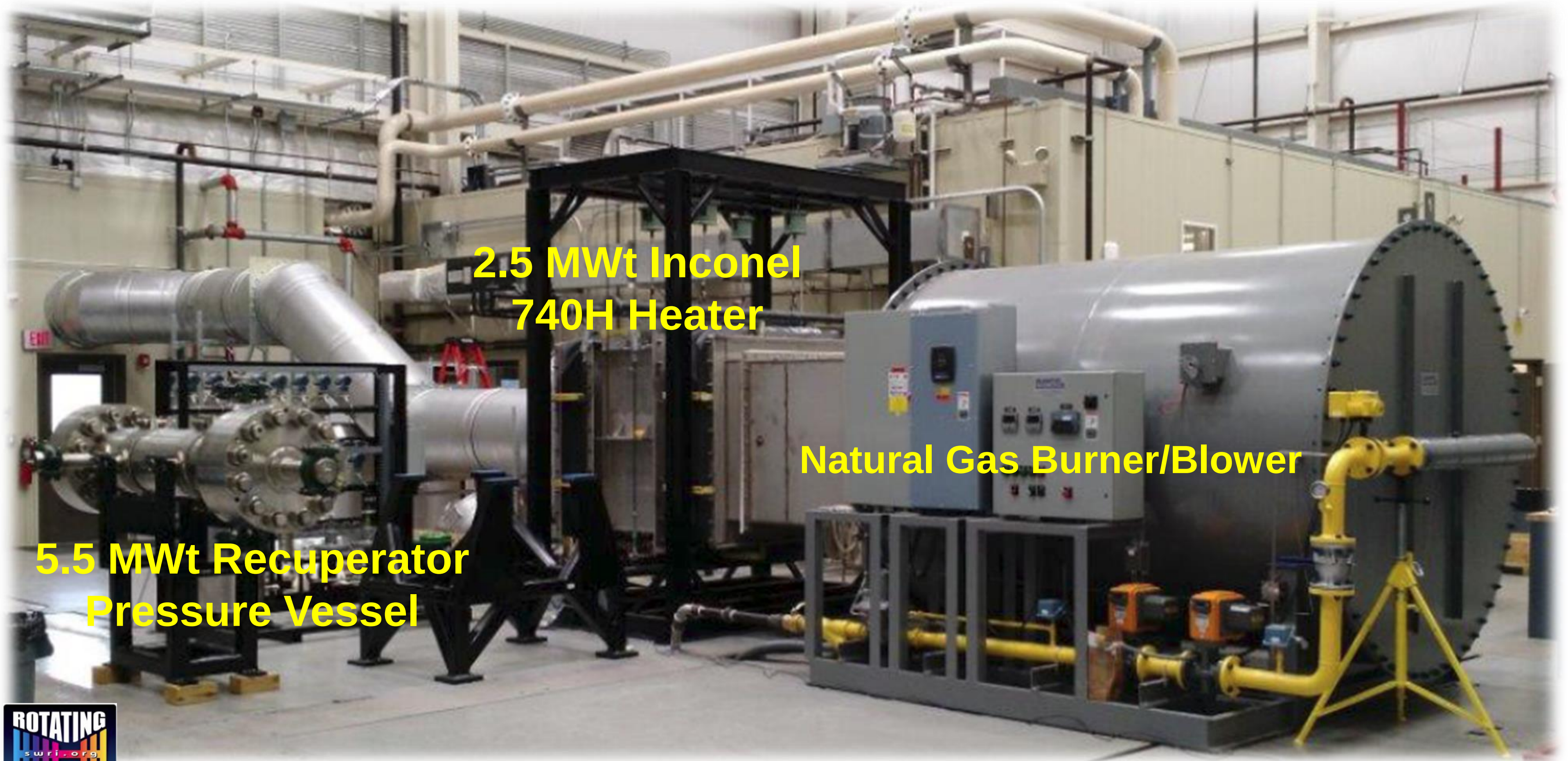
# Installed at SwRI

## *Thar Energy's 2.5MW 740H* Hot Air to $sCO_2$ HX
## *& 5.5 MW $sCO_2$ Recuperator Pressure Vessel*



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# Project and Technology 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

Lalit Chordia, Ed Green, Danyang Li, Peter Shipe, Tom Koger, Marc Portnoff

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

Bruce Pint

Devesh Ranjan, Sandeep Pidaparti

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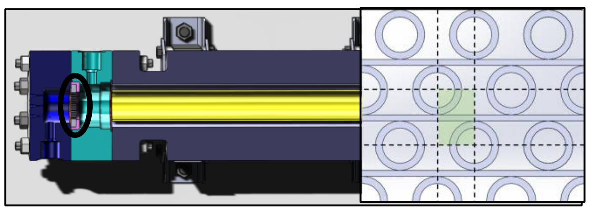
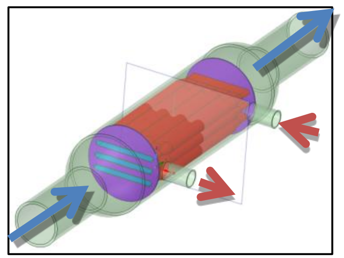
# SOPO Tasks

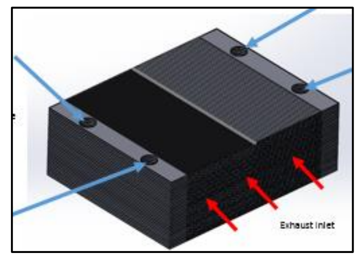
## A scaled prototype will verify the design process and technology before designing for 47 MWt

**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 Schedule

| | Phase 1 | | | | | | Phase 2 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 10/1/15 - 3/31/17 | | | | | | 4/1/17 - 3/31/19 | | | | | | | |
| **Task** | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Q7 | Q8 | Q9 | Q10 | Q11 | Q12 | Q13 | Q14 |
| Task 1.0 - Project management | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Task 2.0 - Engineering Assessment | X | X | X | | | | | | | | | | | |
| Task 3.0 - Preliminary design | | | X | X | | | | | | | | | | |
| Task 4.0 - Prototyping | | | X | X | X | X | | | | | | | | |
| Task 5.0 - Detail Design | | | | | | | X | X | | | | | | |
| Task 6.0 - Recuperator Fabrication | | | | | | | | | X | X | X | X | X | X |

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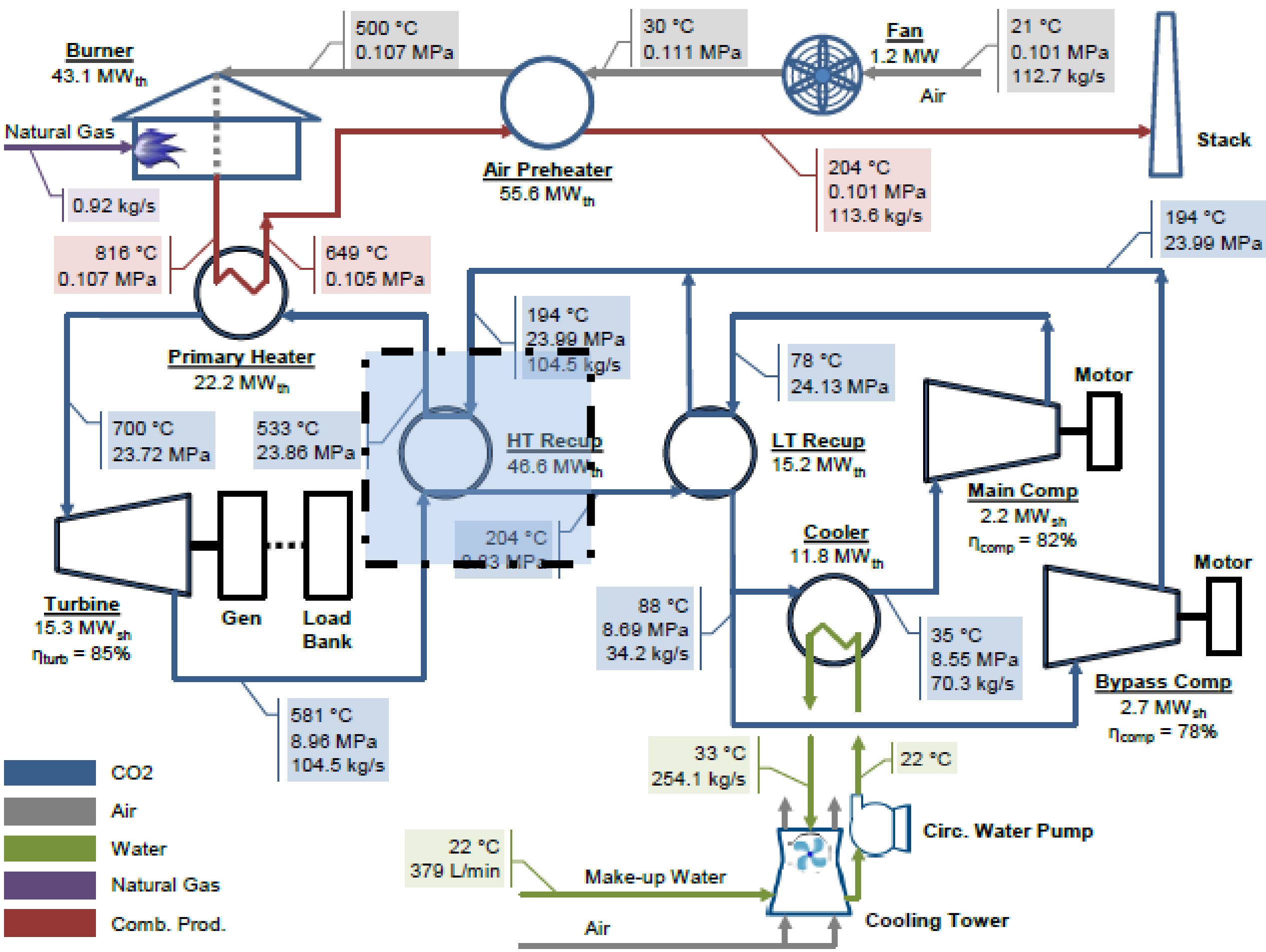
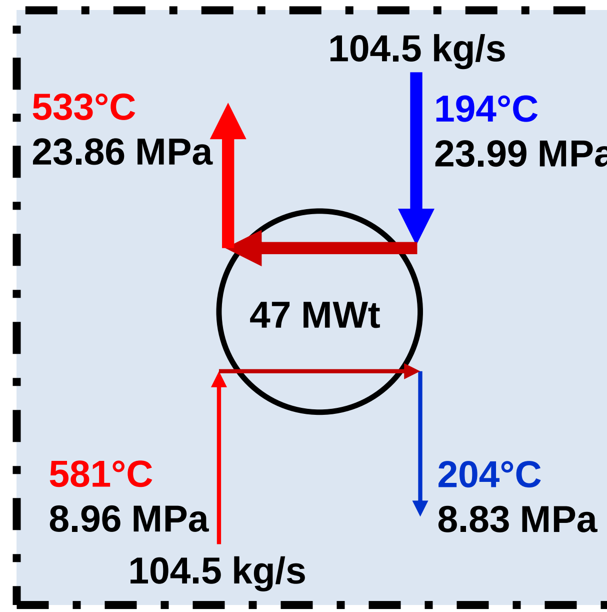
# Develop a Scalable, High Temperature Recuperator for STEP Conditions



# Quantitative Evaluation Criteria
# 47 MWt Recuperator Module
# Used for Concept Down-Select

| Criteria | Metric | Target Value |
|---|---|---|
| **Thermal Effectiveness*** | $\varepsilon = Q_{actual} / Q_{max}$ | $\varepsilon \geq 96\%$ |
| **Pressure Loss*** | $\Delta P = (P_i - P_o) / P_i$ | $\Delta P_c < 1.5\%$ (1.3 bar)<br>$\Delta P_h < 0.6\%$ (1.3 bar) |
| **Temperature Limit*** | Material operating temperature | 581°C |
| **Differential Pressure*** | Pressure difference across high pressure (e.g. 240 bar) and low pressure (e.g. 88 bar) streams | 152 bar |
| **Life** | One or more of: pressure code requirements, fatigue, creep, and corrosion | 30,000 hr |
| **Cost** | $ / kWt | < $100/kWt |
| **Package Dimensions** | Shipping size of the heat exchanger or modular section | 8.8 x 3.6 x 2.6 m |

* Target value estimated from STEP facility process schematic

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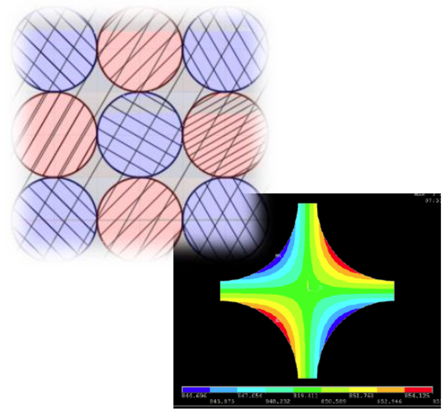
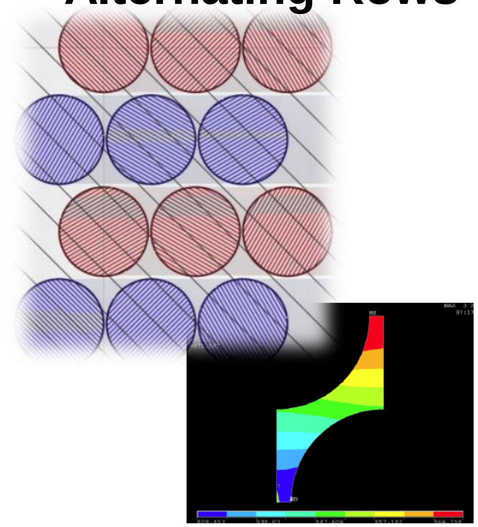
# Heat Exchanger Configuration

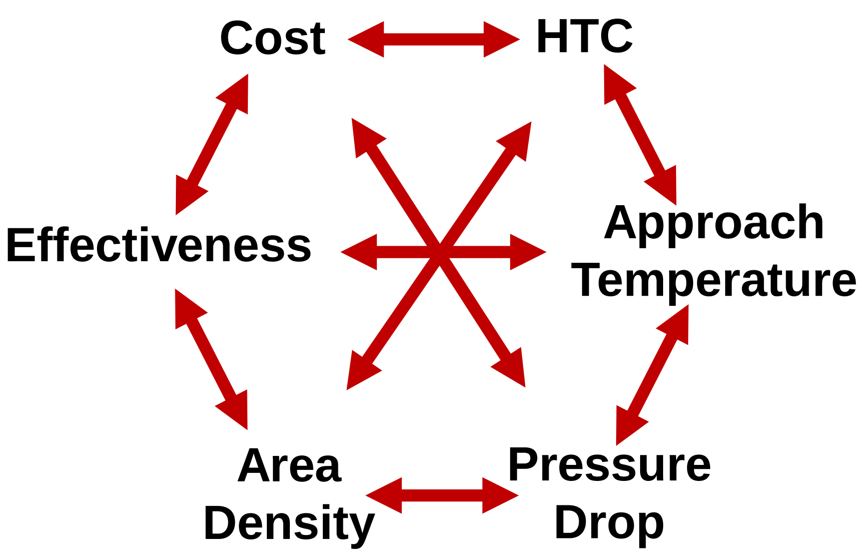
- Area Density (Microchannel passage size)
- Counter Current flow
- Checker Board Flow Pattern
- Passage Shape
- Surface Effects
- Turbulent vs Laminar flow

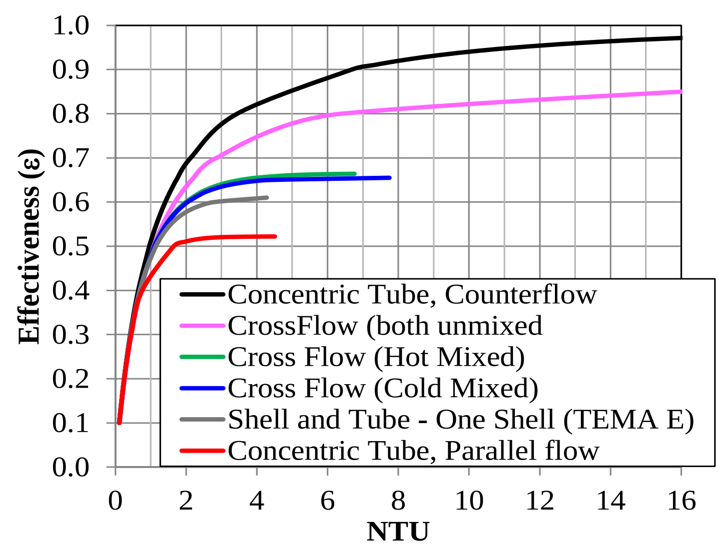
Checkerboard



Alternating Rows





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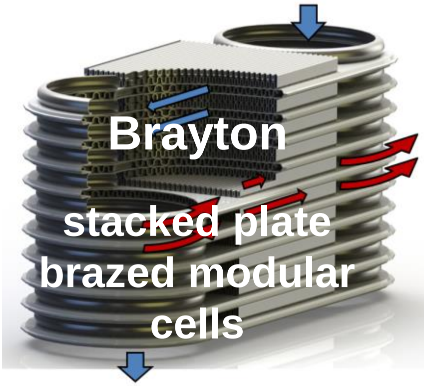
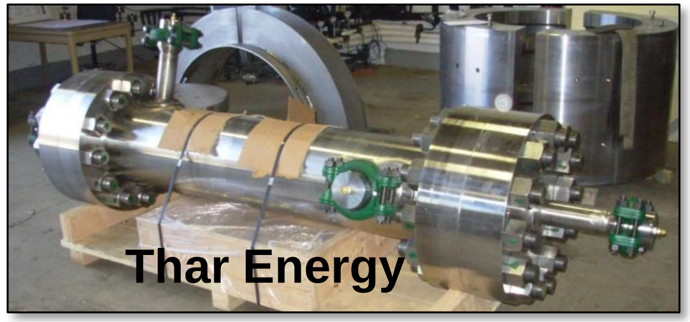
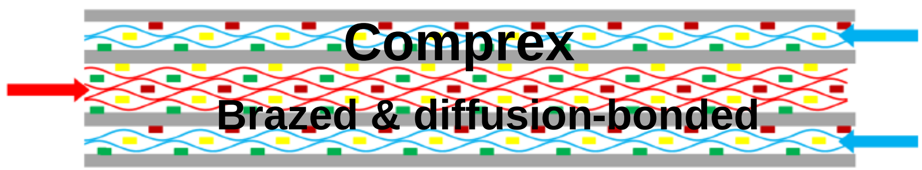
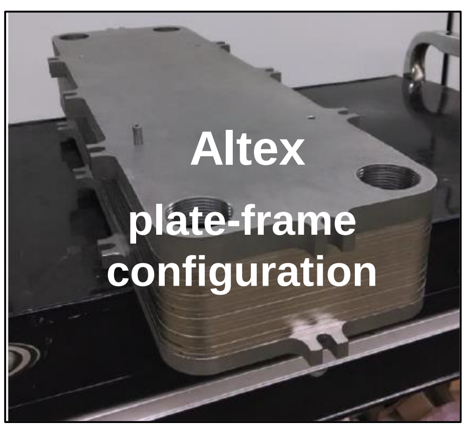
# State-of-the-art $sCO_2$ HX were reviewed in detail





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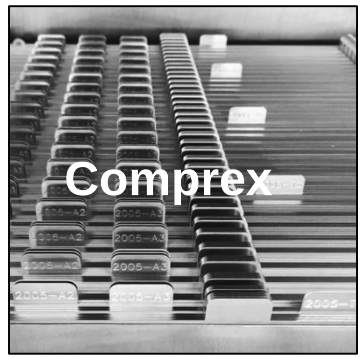
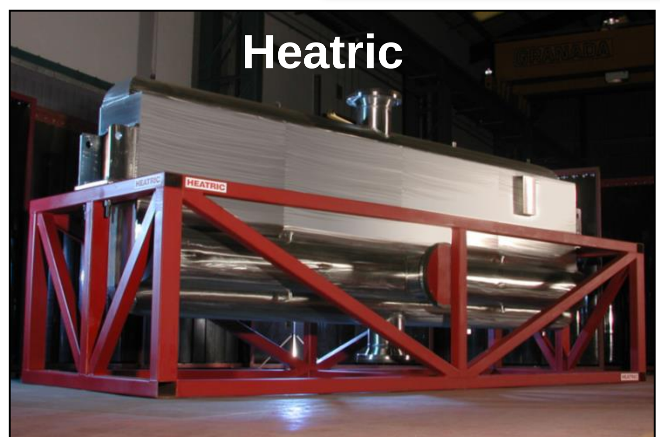
# Insufficient information in the literature, concerning state-of-the-art $sCO_2$ plate-type (brazed or diffusion-bonded) HXs, to meet project criteria:

**47MWt, 240 bar, 581°C, 96% Effectiveness, $\Delta P$ < 1.3 bar, <$100kW**



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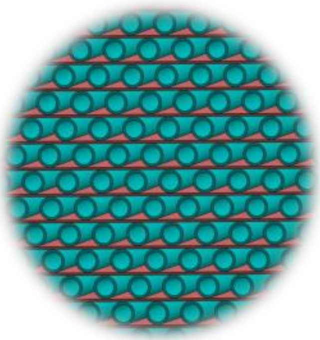
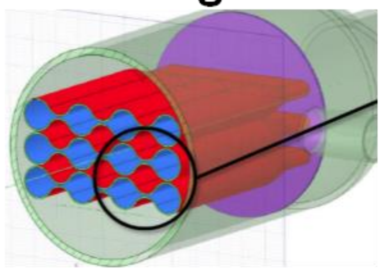
# Recuperator Concepts Selected from Brain Storming

**Microtube**



**Corrugated**



**Helical**

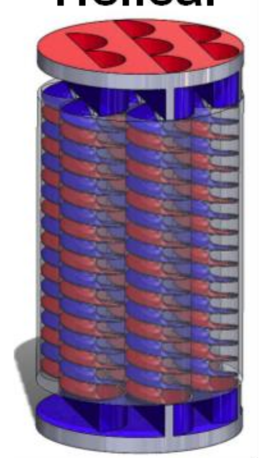
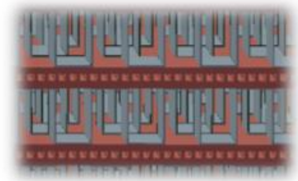
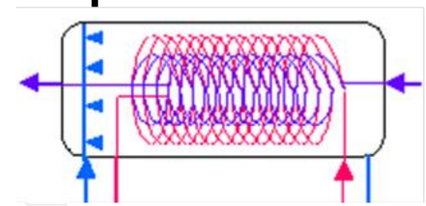


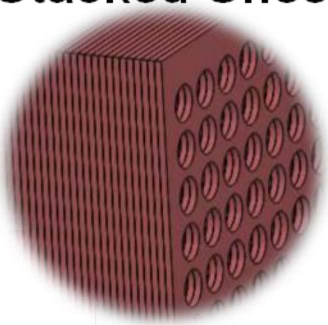
**Plate-Fin**



**Spiral-Wound**



**Stacked-Sheet**



**Liquid Metal Bath**

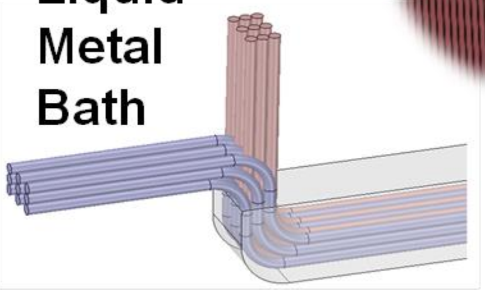
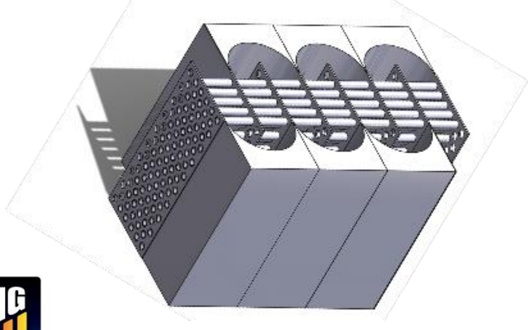
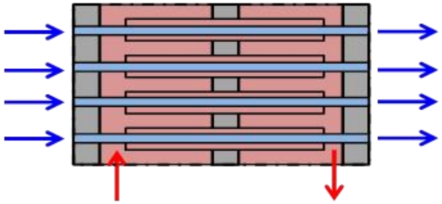


**Plate-crossflow**



**Double-pipe**



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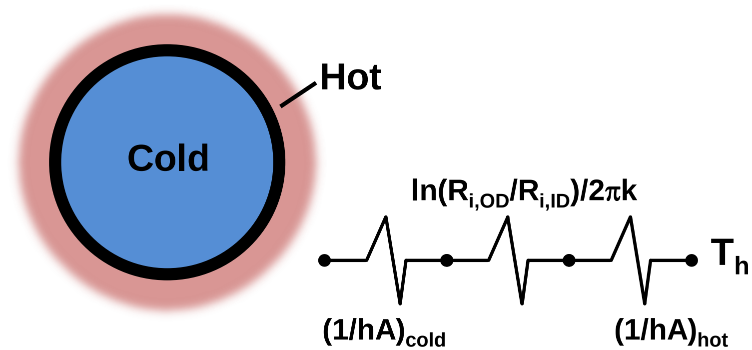
# One-dimensional methods are used for conceptual sizing the heat exchanger cores at 47 MWt scale

| Criteria | Metric | Target Value |
|---|---|---|
| **Thermal Effectiveness** | $\varepsilon = Q_{actual} / Q_{max}$ | $\varepsilon \geq 96\%$ |
| **Pressure Loss** | $DP = (P_i - P_o)$ | $DP_c < 1.3$ bar<br>$DP_h < 1.3$ bar |
| **STEP Pressure & Temperature** | 24MPa – 194°C & 9MPa – 581°C | |

## 1) Assume constant thermal properties to find the required overall heat transfer coefficient (UA)

$$NTU = \frac{1}{C_{min}/C_{max} - 1} ln\left(\frac{\varepsilon - 1}{\varepsilon\, C_{min}/C_{max} - 1}\right)$$

$$UA = NTU * C_{min} = 1{,}597\ kW/K$$




## 2) If available, use a discretized model to achieve the required thermal duty (47 MWt)

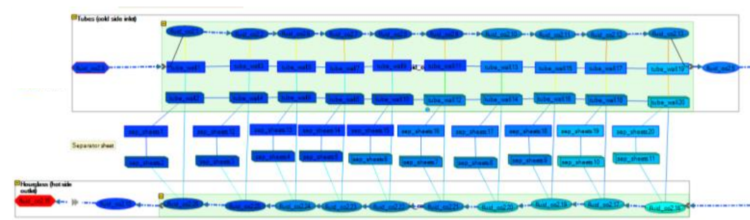
# Concept Evaluation using 1-D Thermal Fluid Modeling

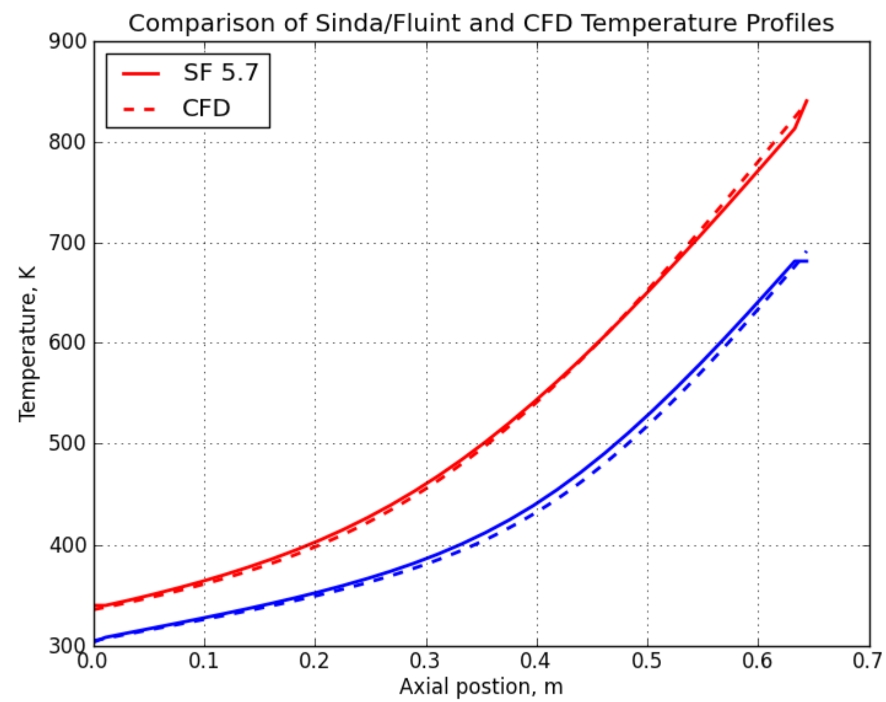
## Pros

- Computationally efficient
- Scalable
- Flexible
- System level performance information

## Cons

- Reduced order fidelity
  - Does not provide details on the physics
- Relies on other sources for some information (i.e. HTC from CHT)





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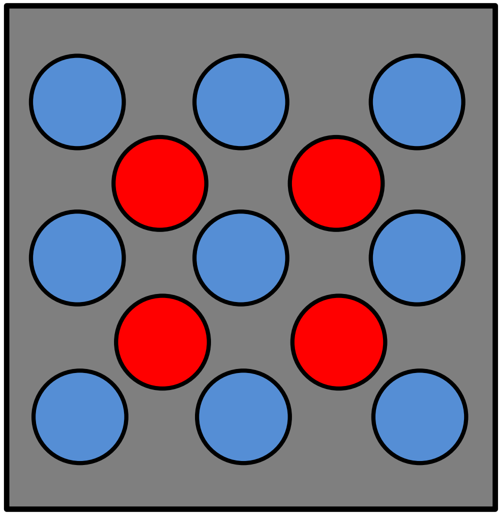
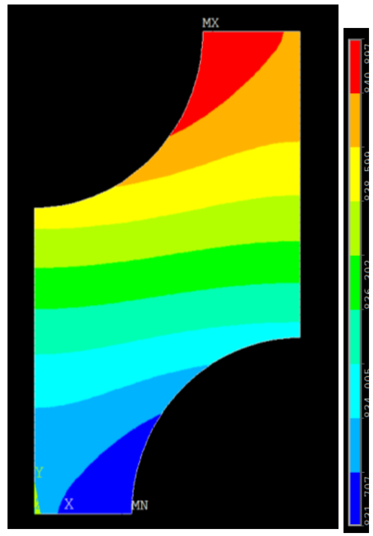
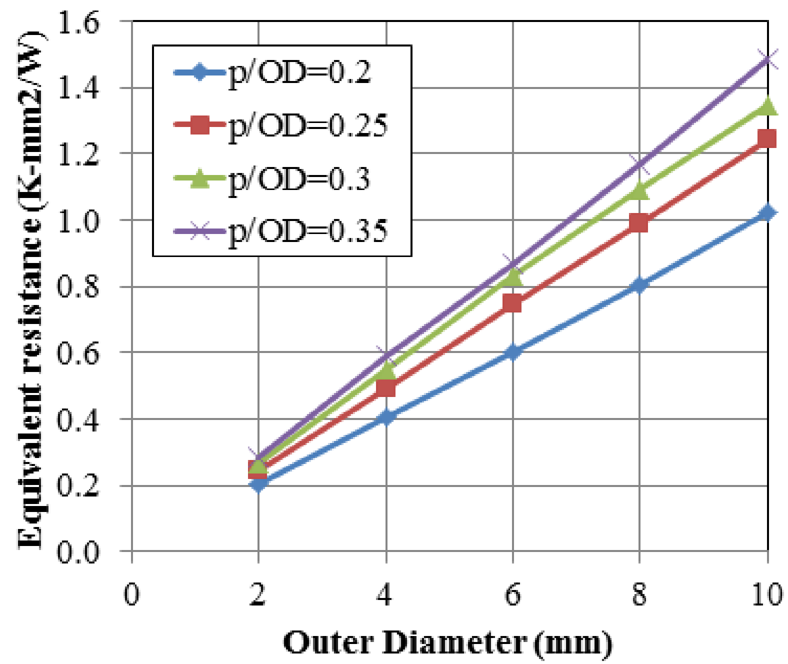
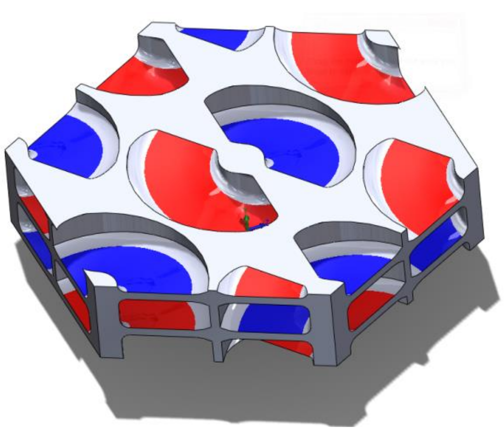
# ANSYS thermal models are used to account for complex thermal circuits

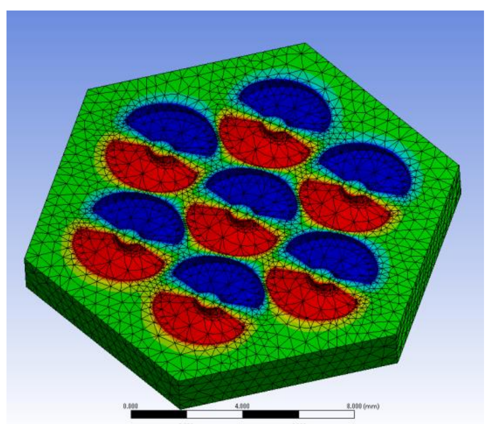




567°C
563°C
558°C





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# Heat exchanger cost is estimated from the size of the major material components

- Equivalent $/lb material costs are usually based on Thar & SwRI past experience:
  - ❖ Tubes
  - ❖ Casing
  - ❖ Flanges
  - ❖ Sheets
- Multiple vendor quotes are correlated for estimating cost of specific features:
  - ❖ $/Area for formed sheets
  - ❖ $/Hole – Conventional vs. EDM drilling
  - ❖ Hole punching
  - ❖ Chemical etching
  - ❖ Brazing
  - ❖ Diffusion Bonding

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# 47 MWt Recuperator Concept Comparison

- **Model each Recuperator Concept, at the 47 MWt scale, for performance:**
  - ❖ **96% Effectiveness, $\Delta P$ < 1.3 bar, 581°C & 240 bar per ASME Code**

- **Determine Recuperator Size & Cost:**
  - ❖ **Does it meet the cost criteria, <$100/kWt?**

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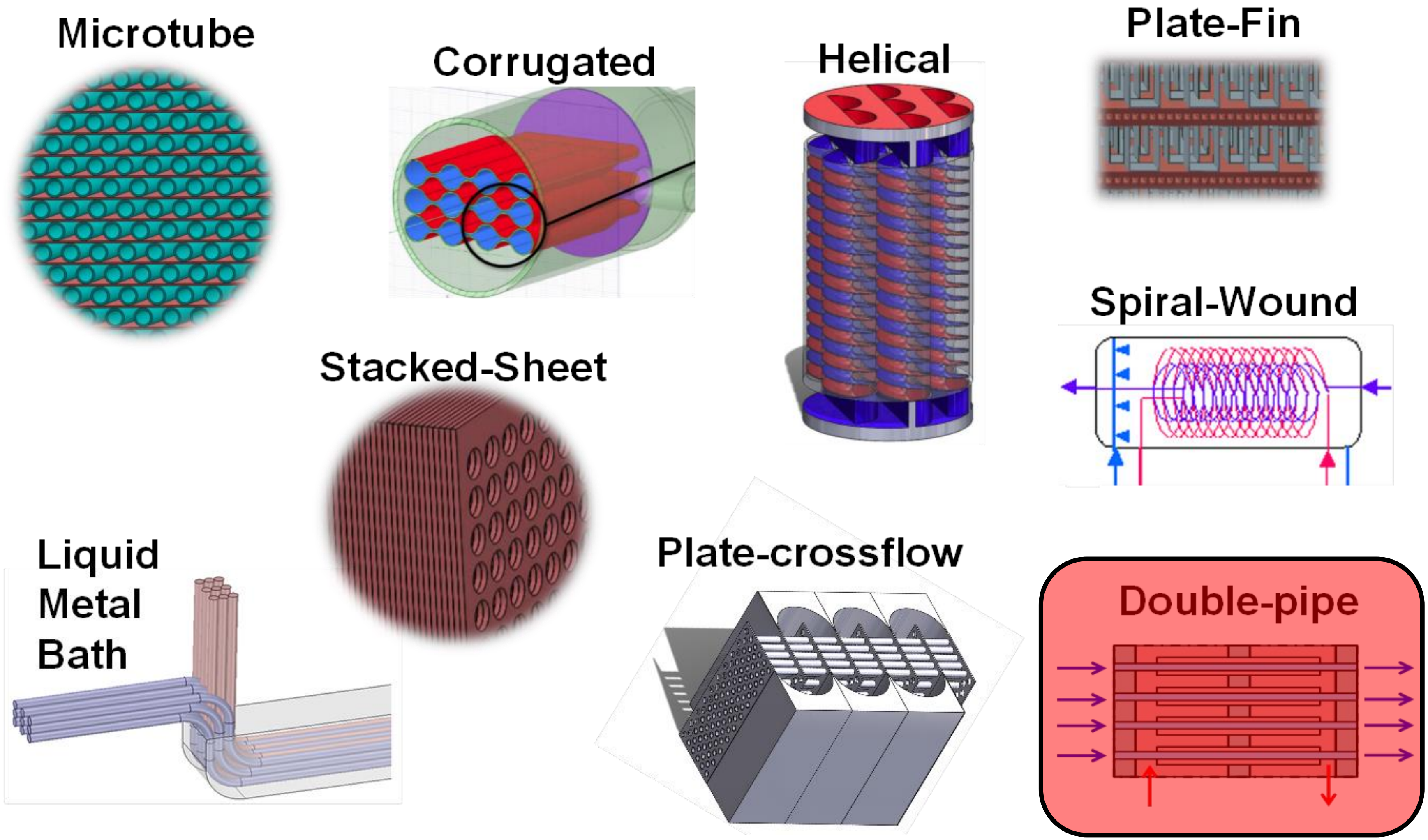
# The double-pipe increased frictional loss without increasing heat transfer



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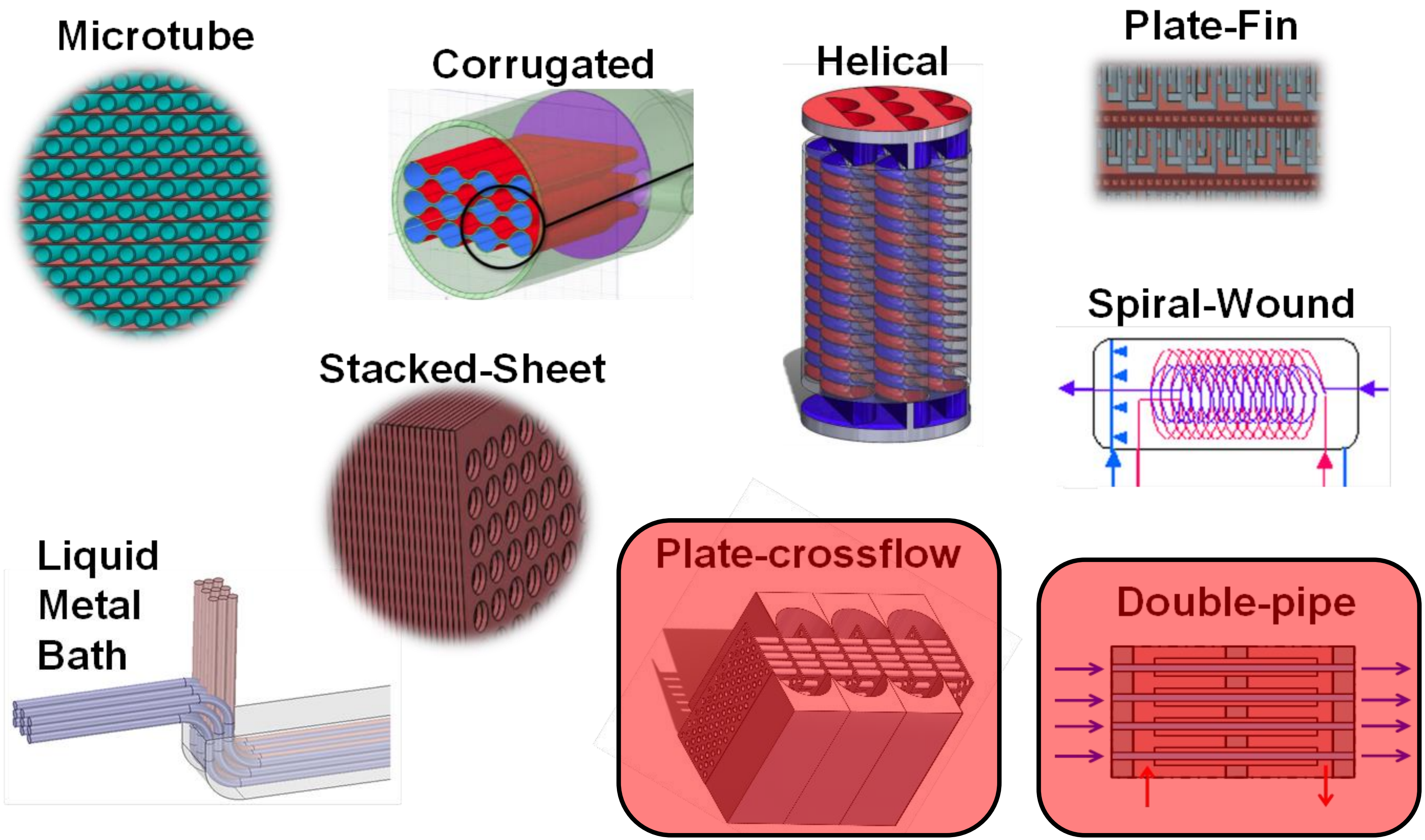
# Relative to the microtube, the plate-crossflow increases complexity and tube count



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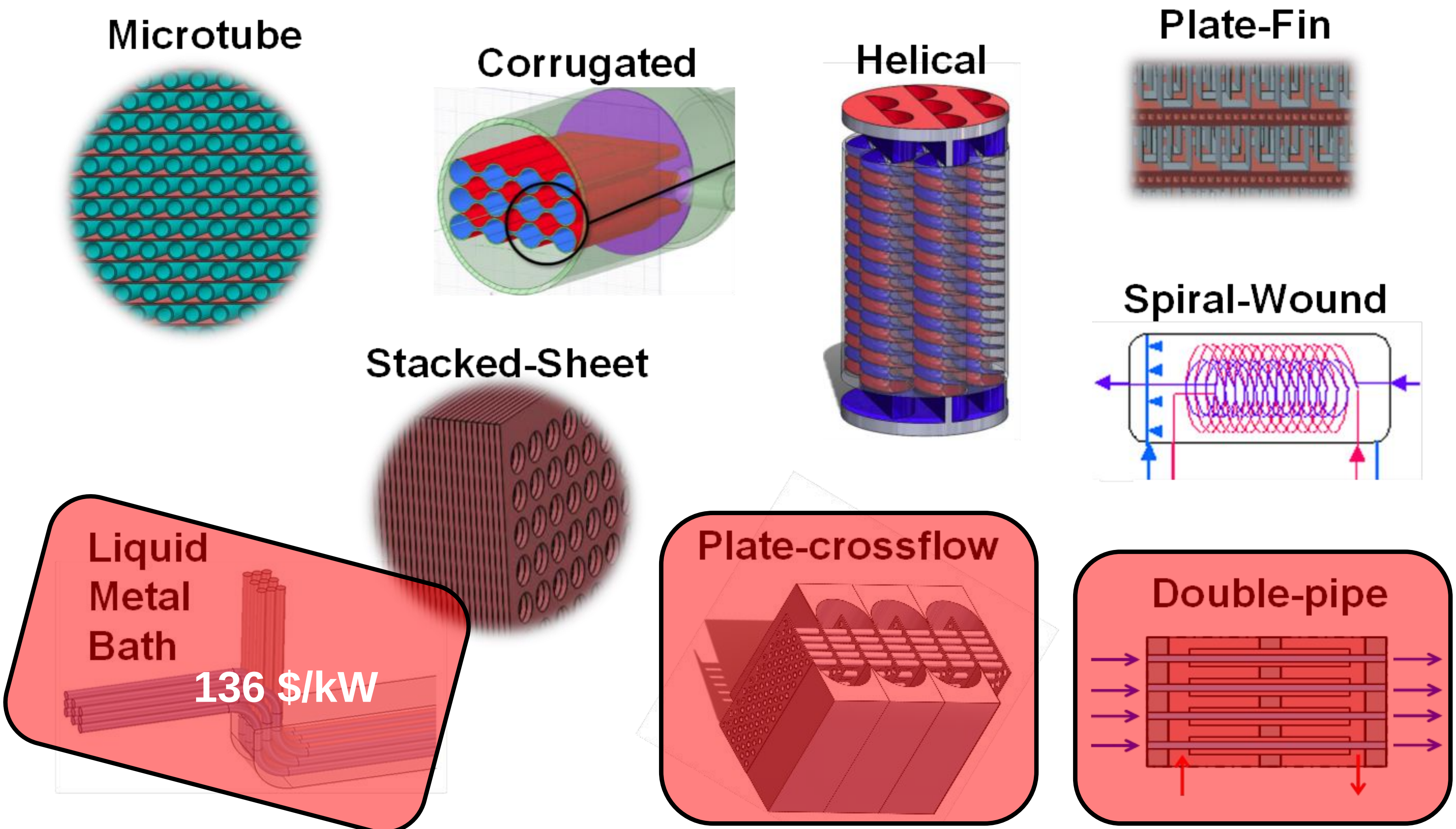
# The liquid metal bath concept has a high cost due to the manifold arrangement and number of tubes



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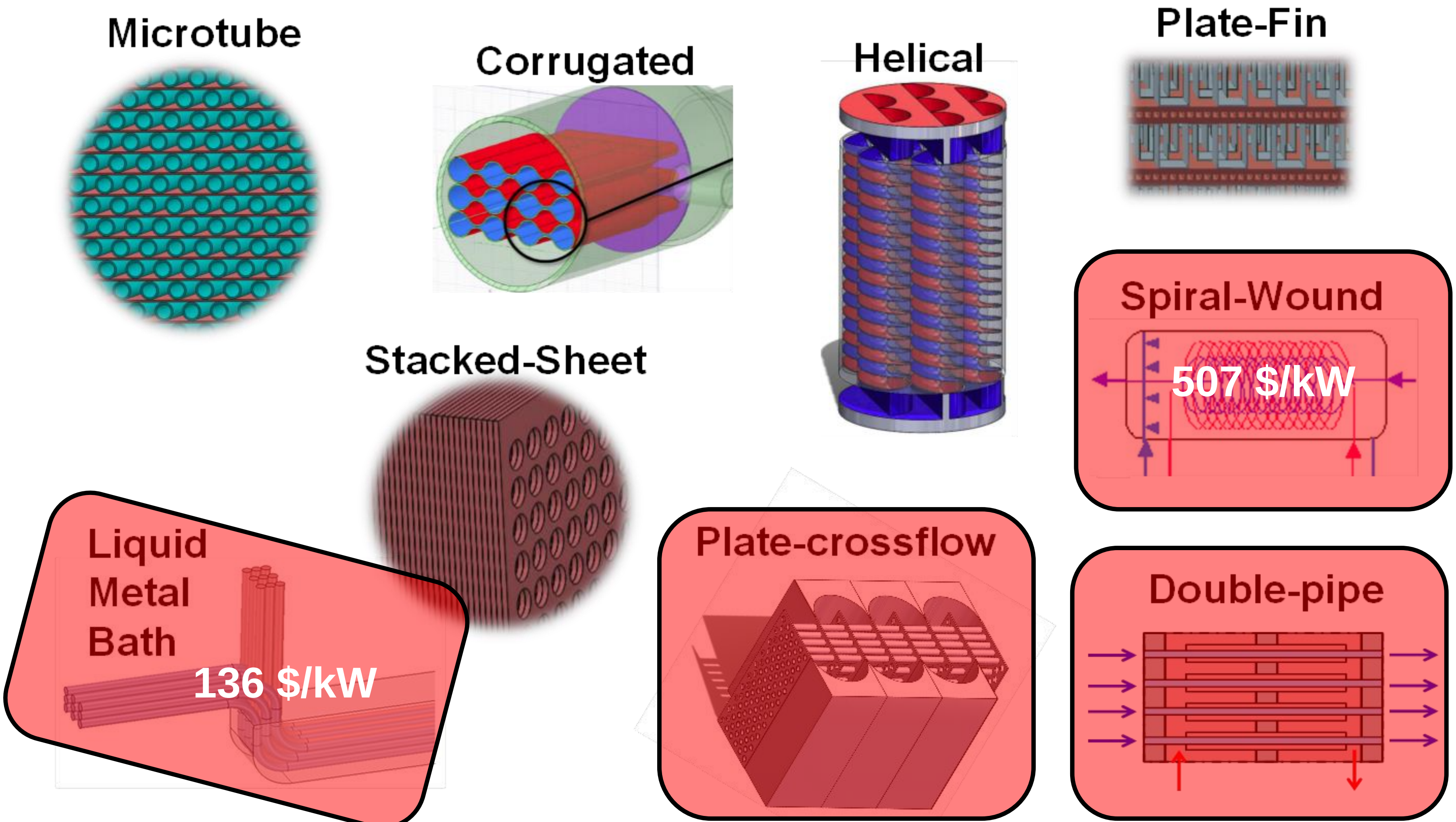
# The spiral-wound requires large tubes and long lengths, resulting in high material costs



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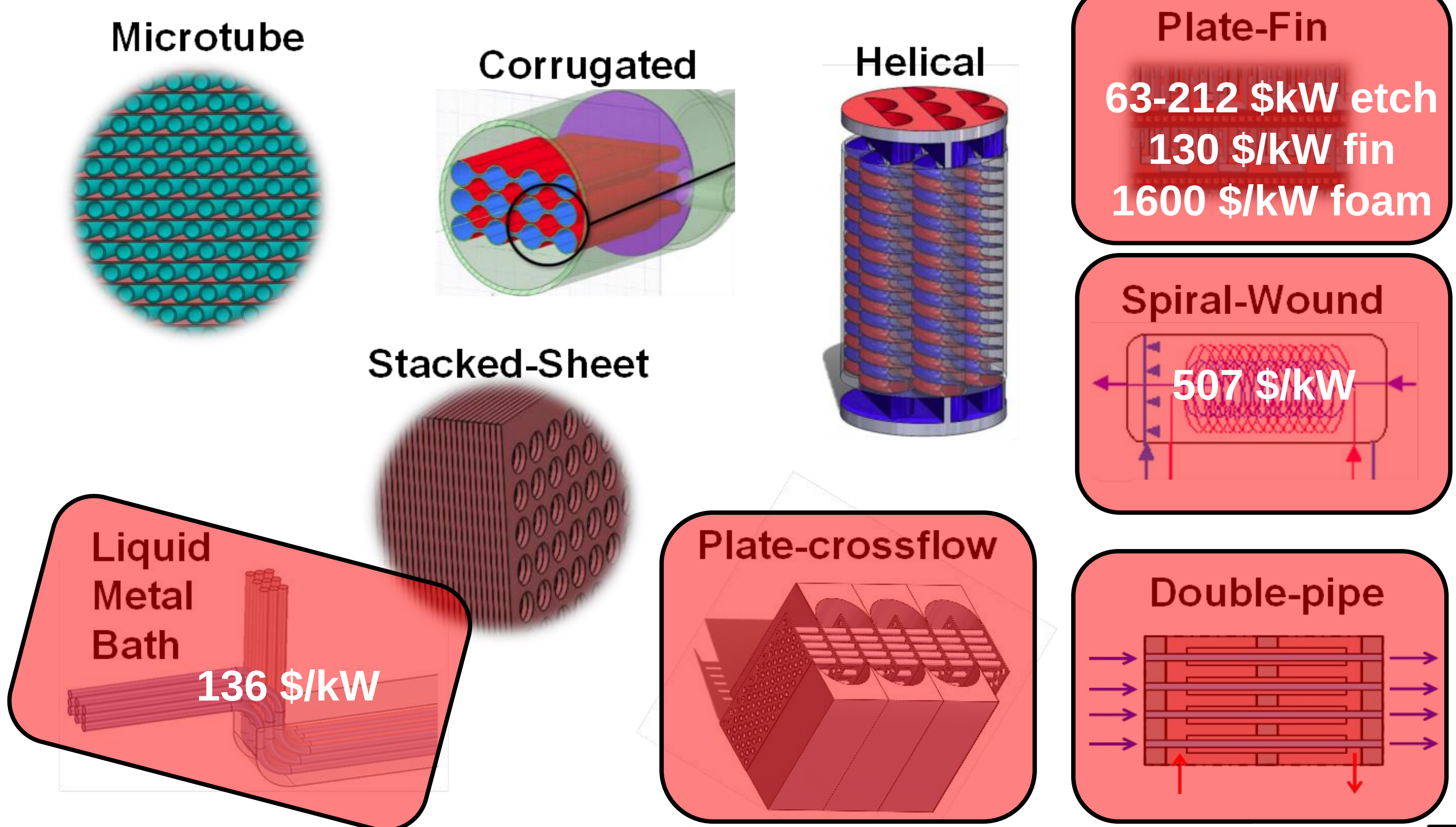
# Plate-Fin, Plate-Foam, & Etched Plate-Fin concepts were too expensive



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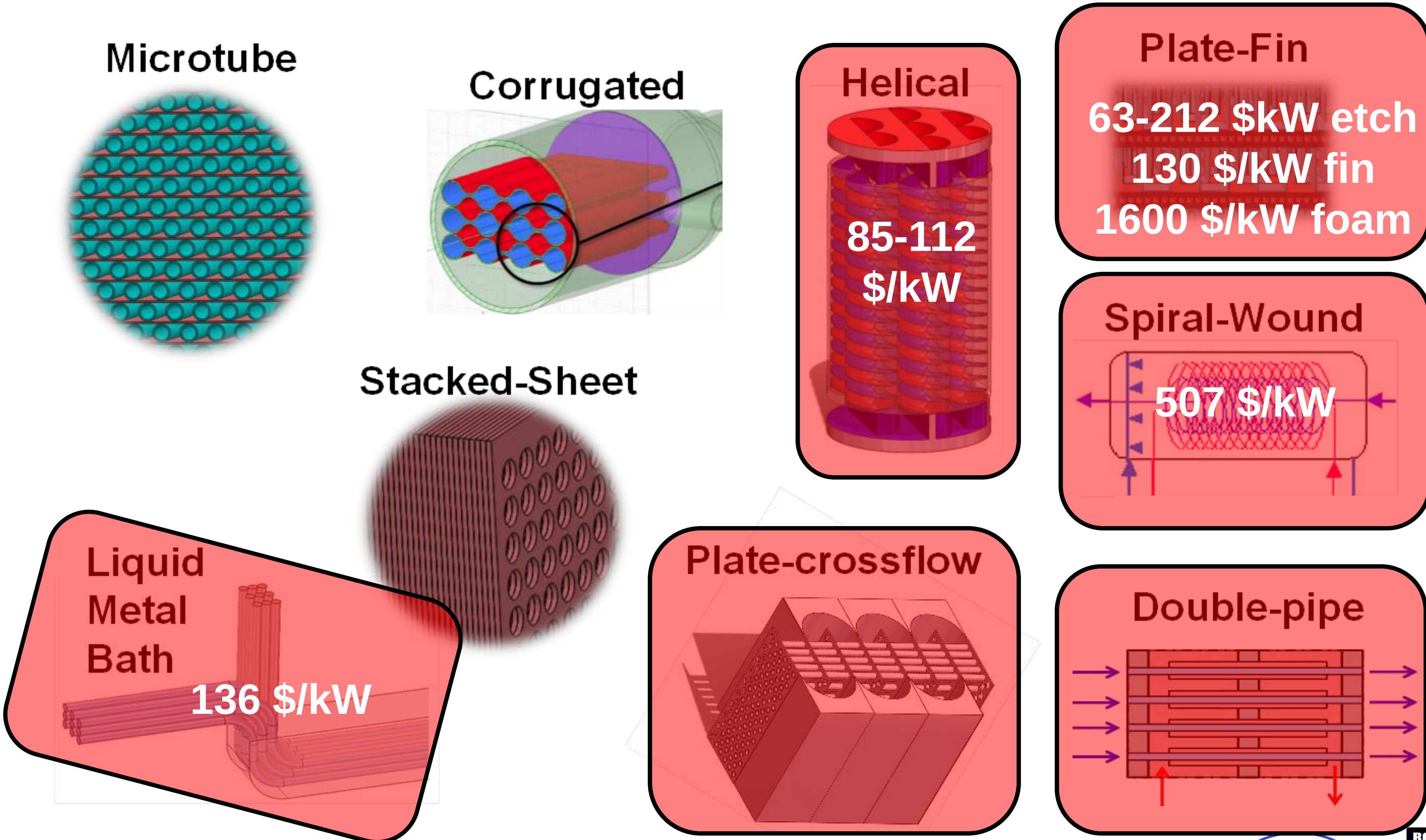
# The Helical concept had uncertainty in design and manufacturability in addition to a high cost



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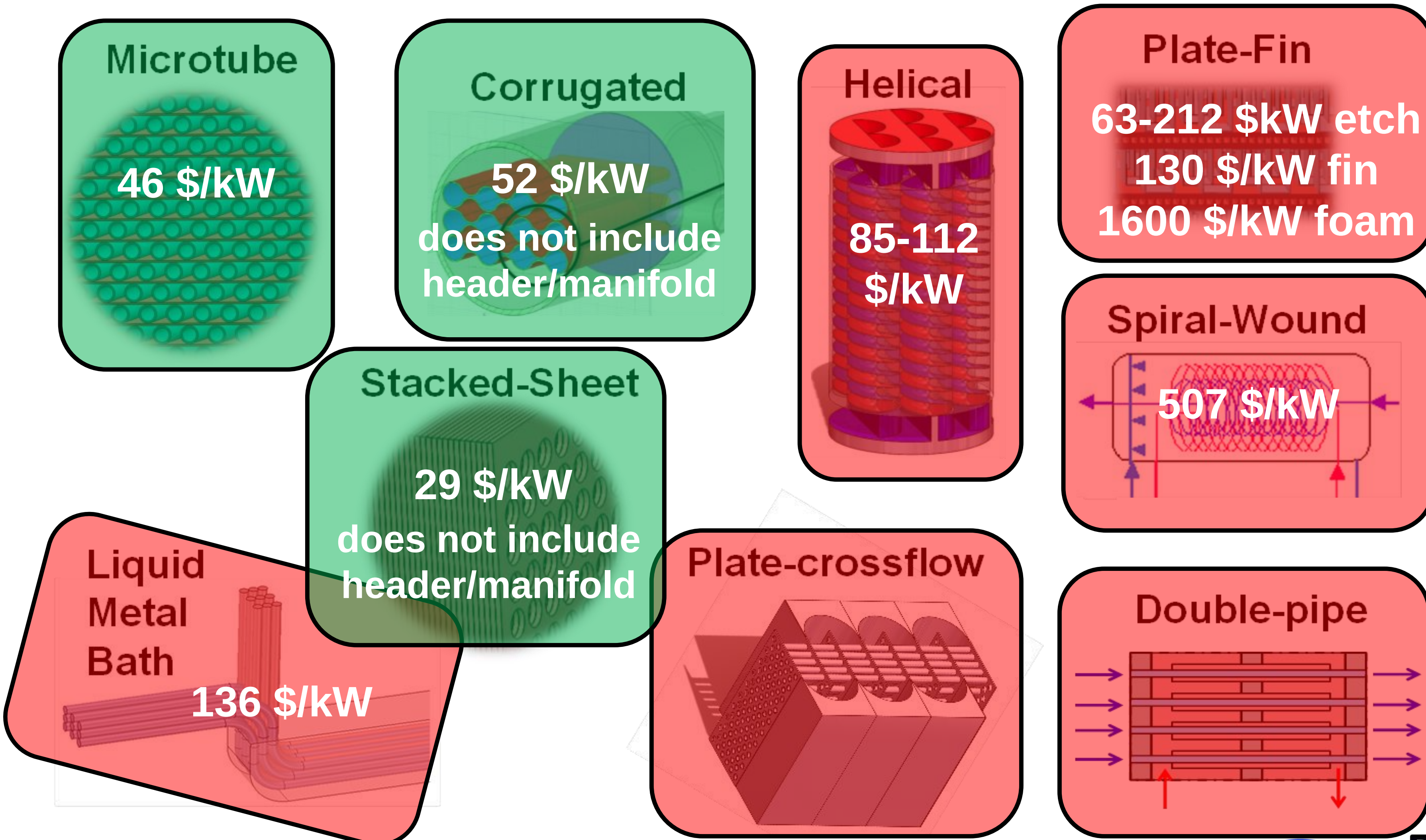
# The Microtube, Corrugated & Stacked-Sheet Recuperator Concepts were down selected for low complexity and cost



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# Preliminary Engineering is performed on the three down-selected recuperator concepts

**Includes:**

- **overall system performance**
- **cost**
- **flow path design**
- **detailed analysis of critical design features**
- **material selection**
- **design for manufacturing to ASME code**
- **design for operation and maintenance.**

***Incorporate header & manifold designs in all concepts***

**Using:**

- **Fluid-thermal network analysis or bulk properties finite element analysis (FEA) to evaluate recuperator performance, as well as to facilitate the optimization of recuperator modules.**
- **Computational fluid dynamics (CFD), FEA, and conjugate heat transfer (CHT) to establish heat transfer coefficient and pressure loss**
- **Material properties such as yield strength, creep strength, and corrosion resistance**

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# Considerations for Updating Recuperator Criteria

- **Effectiveness Rating: 92-96%**
    - ❖ Effect on HX size and Cost
- **Rated Design Point**
- **Fouling Potential:**
    - ❖ Particle size vs. channel passage size
    - ❖ Cost of larger recuperator vs. use of filters

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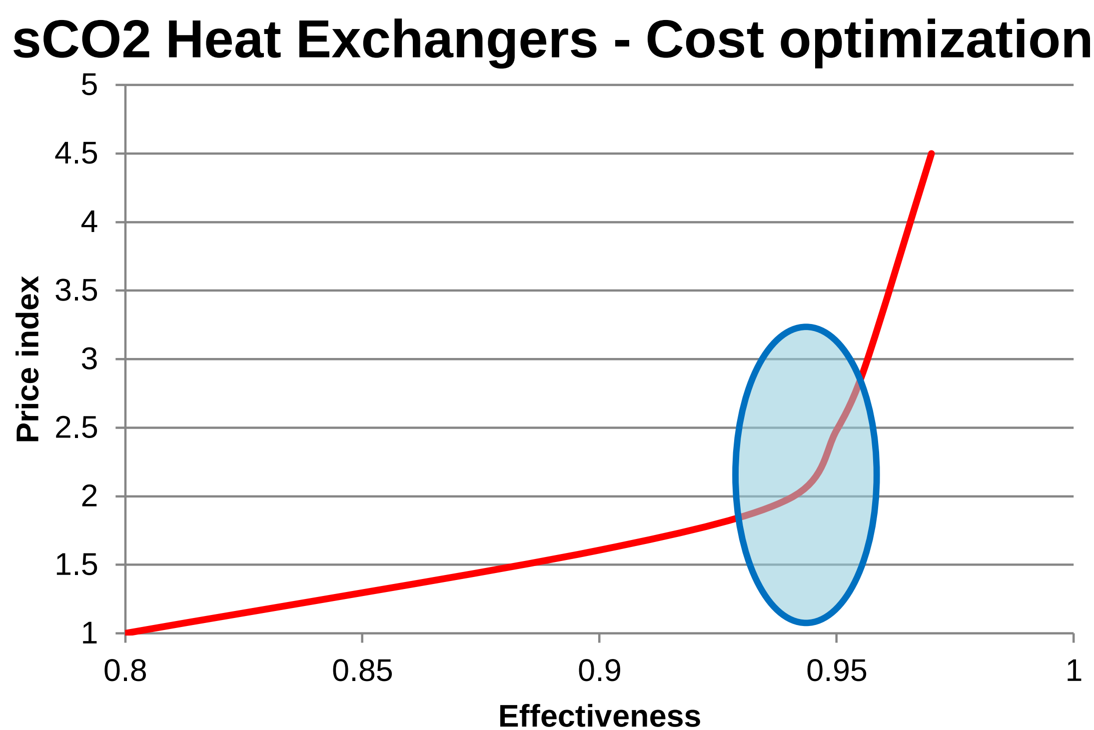
# Recuperator Criteria Considerations

***Effectiveness rating requirements can have a dramatic impact on HX size and cost***




**Le Pierres, R., Heatric, Industry Panel Session, 5th International Supercritical CO2 Power Cycles Symposium**

# Selected Alloy Properties

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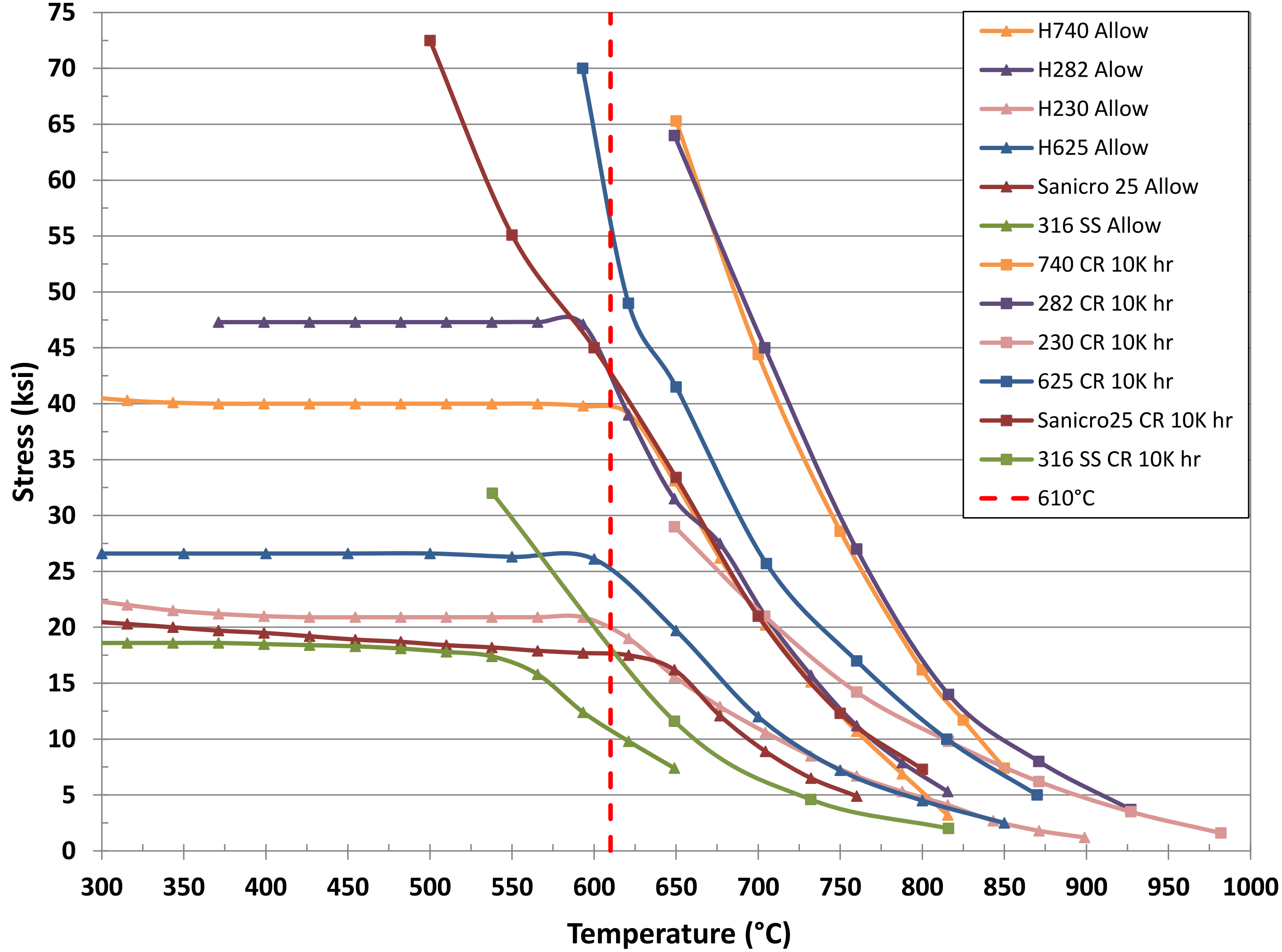
## ASME Allowable Stress and 10,000 Hour Creep Rupture Values

***Higher Design T increases costs faster than Design P due to material strength reduction & increased corrosion rates***



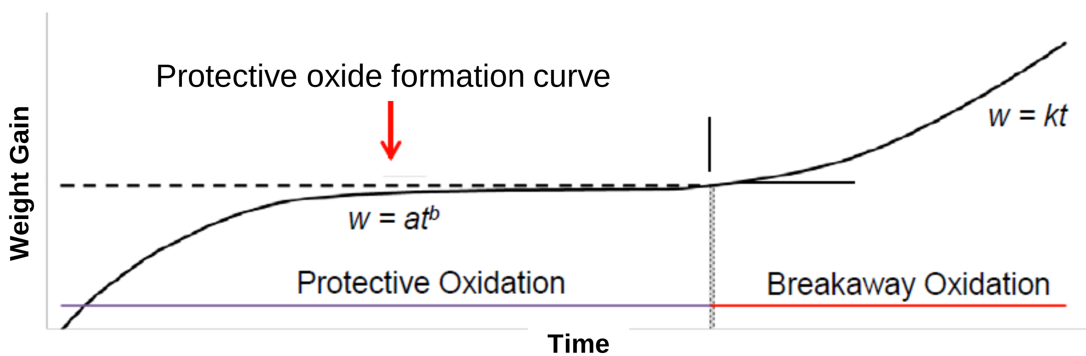
# $sCO_2$ Power Cycle - Alloy Corrosion

**ORNL's guidance of corrosion at STEP conditions**

## Corrosion is not expected to be a problem for:

- **Stainless Steel Alloys below 550°C**
- **Nickel Alloys below 650°C**

## 30K hour corrosion allowance: 1 mil (25.4 µm)



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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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# 47MWt Microtube Recuperator Fabrication

*Discussions with numerous vendors have been initiated*

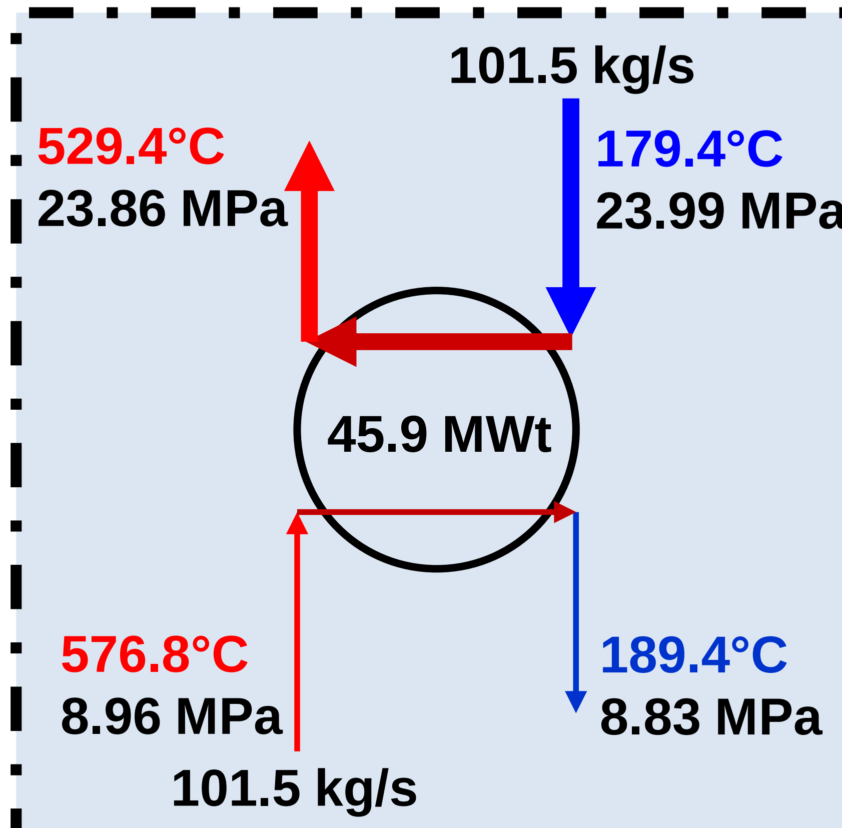
## Advanced Manufacturing

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


# 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



# Comparison of Recuperator Design Criteria

| Criteria | Initial | Updated |
|---|---|---|
| Thermal Effectiveness | **96%** | **97%** |
| Pressure Loss | $\Delta P_c$ < 1.3 bar<br>$\Delta P_h$ < 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 | |

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# Outline

- Introduction to Thar Energy

- Project Overview
  - Objectives
  - Participants
  - Task Summary

- Project Update
  - STEP Recuperator Criteria
  - $sCO_2$ Recuperator Concepts
  - Down-Selection Process
  - Preliminary Engineering Analysis
  - Recuperator Criteria - Updated
  - Preliminary Engineering Findings
  - Prototype Design, Fabrication & Testing
  - Closing Summary

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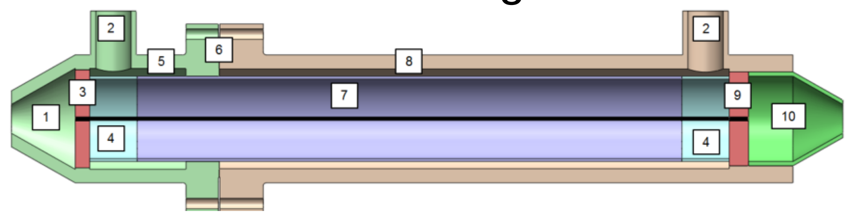
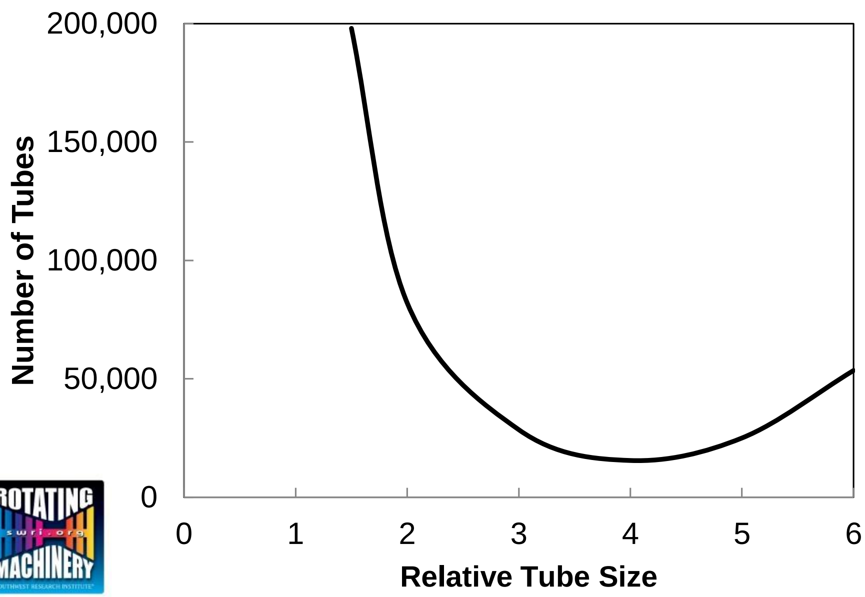
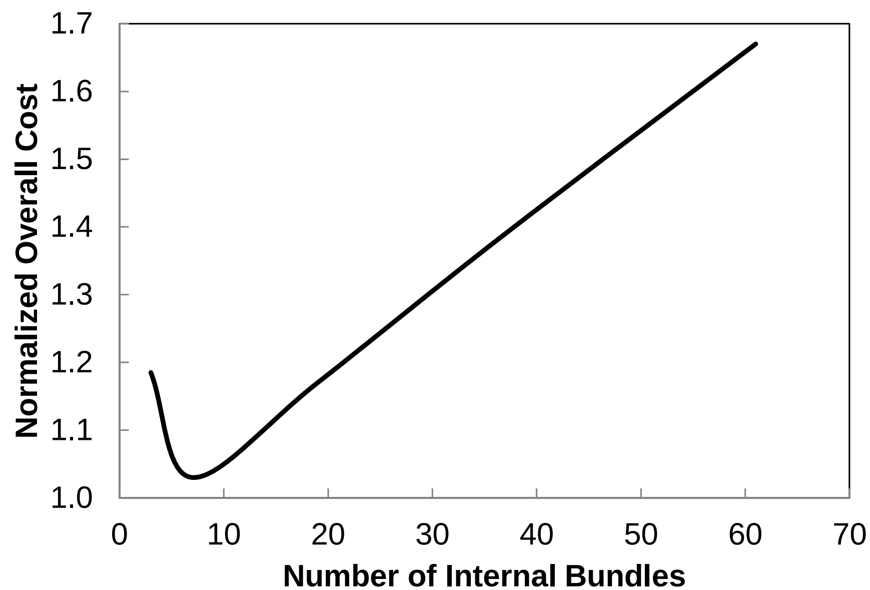
# Microtube Recuperator – evaluate how relationships between design parameters allow for cost reduction while meeting performance goals

## Design Parameters
- Number of tubes
- Tube diameter
- Tube length
- Tube spacing

## Effects on Size and Cost
- Casing diameter and thickness
- Tube sheet thickness
- Tube sheet manufacturing cost



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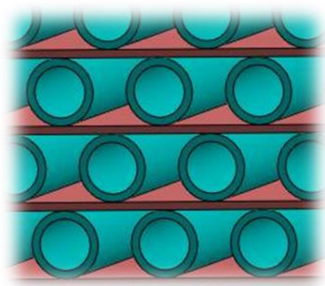
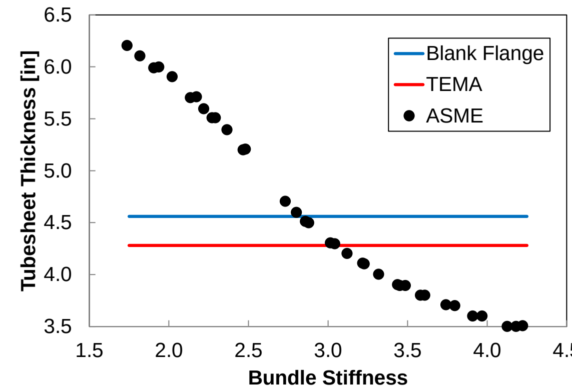
# Microtube Recuperator - updates are made to the thermal-hydraulic performance calculations

Improve fidelity for effects of separator sheets

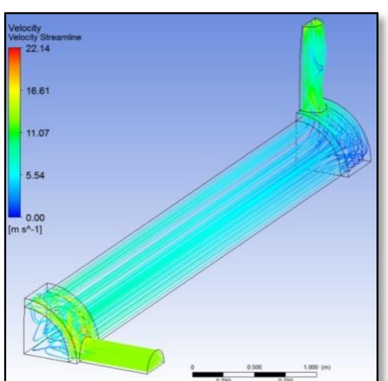
- Pressure drop
- Heat transfer area



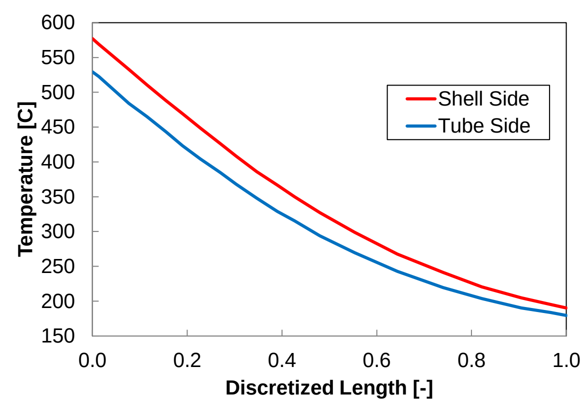
Include ASME code calculations for tube sheet and casing




One-dimensional pressure drop calculations confirmed with reduced-order CFD model




Discretized one-dimensional model to account for varying fluid properties



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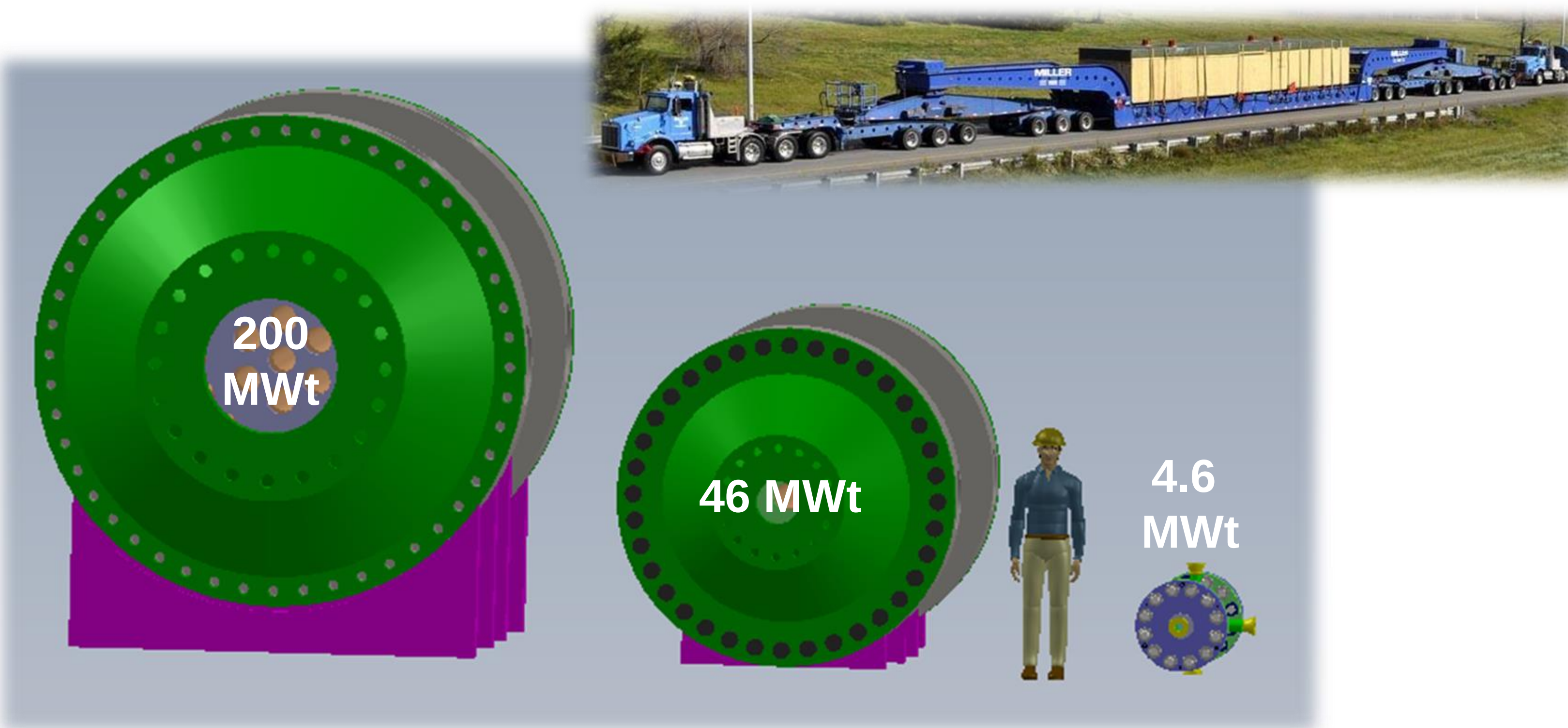
# Microtube Recuperator

## Modular tube bundle is preferred to single module design

- Removable tube bundles for maintenance and repair
- Each tube bundle has is own floating tube sheet
- Each tube bundle has its own pressure boundary
- Economies of scale lower the modular tube bundle costs
- 200 MWt unit meets shipping criteria



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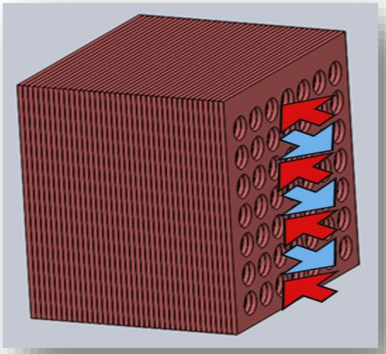
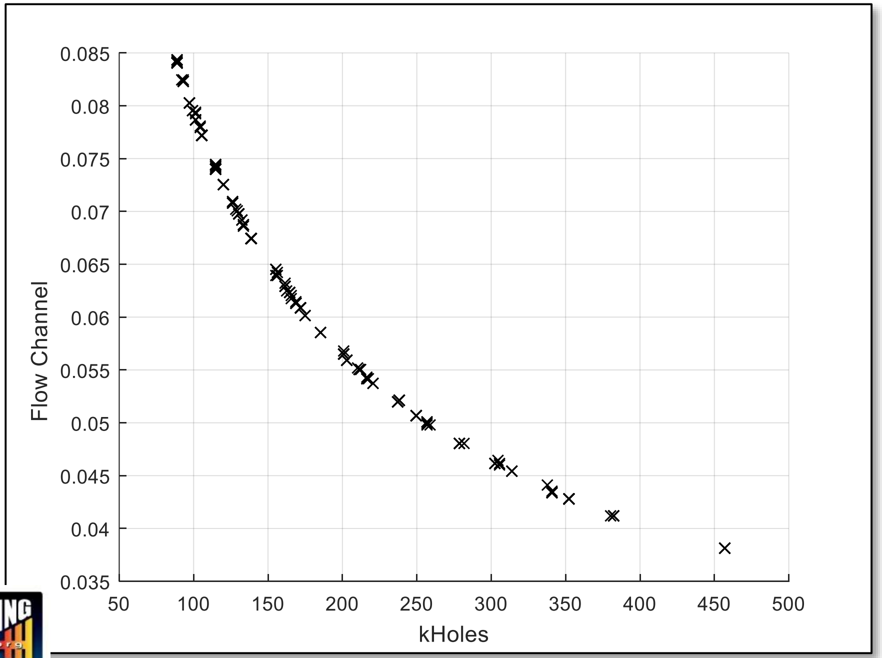
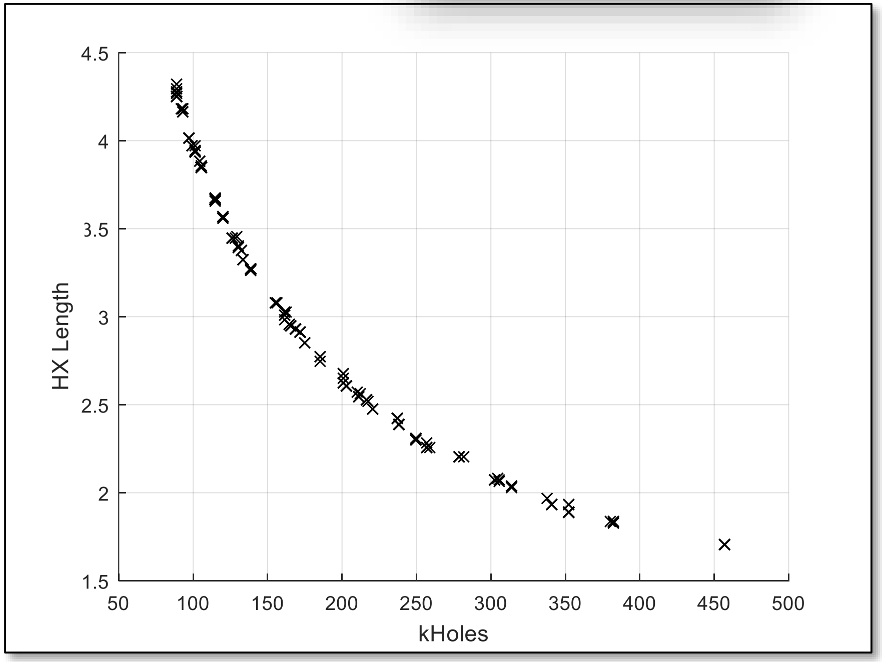
# The Stacked-Sheet Recuperator Concept has similar design relationships to the Microtube Concept

**Design Parameters**
- Number of passages
- Passage diameter
- Passage length
- Passage spacing

**Effects on Size and Cost**
- Overall dimensions
- Sheet thickness
- Manufacturing limits





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# The critical components in the design are the manufacturability and pressure containment

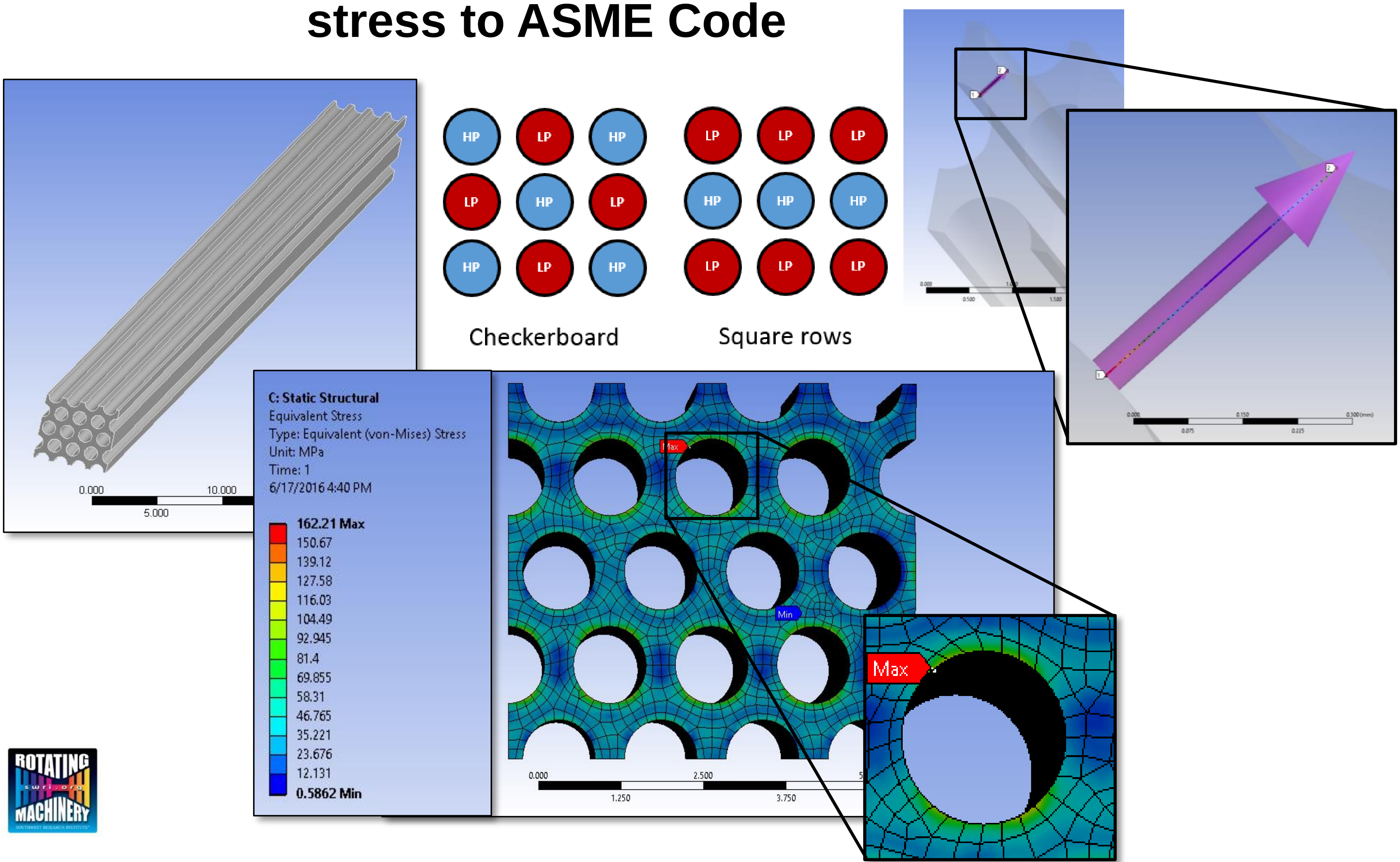
**Manufacturability effects:**

- Surface roughness characteristics in the passages
- Alignment of sheets and manufacturing tolerances
- Diffusion bonding vs. brazing

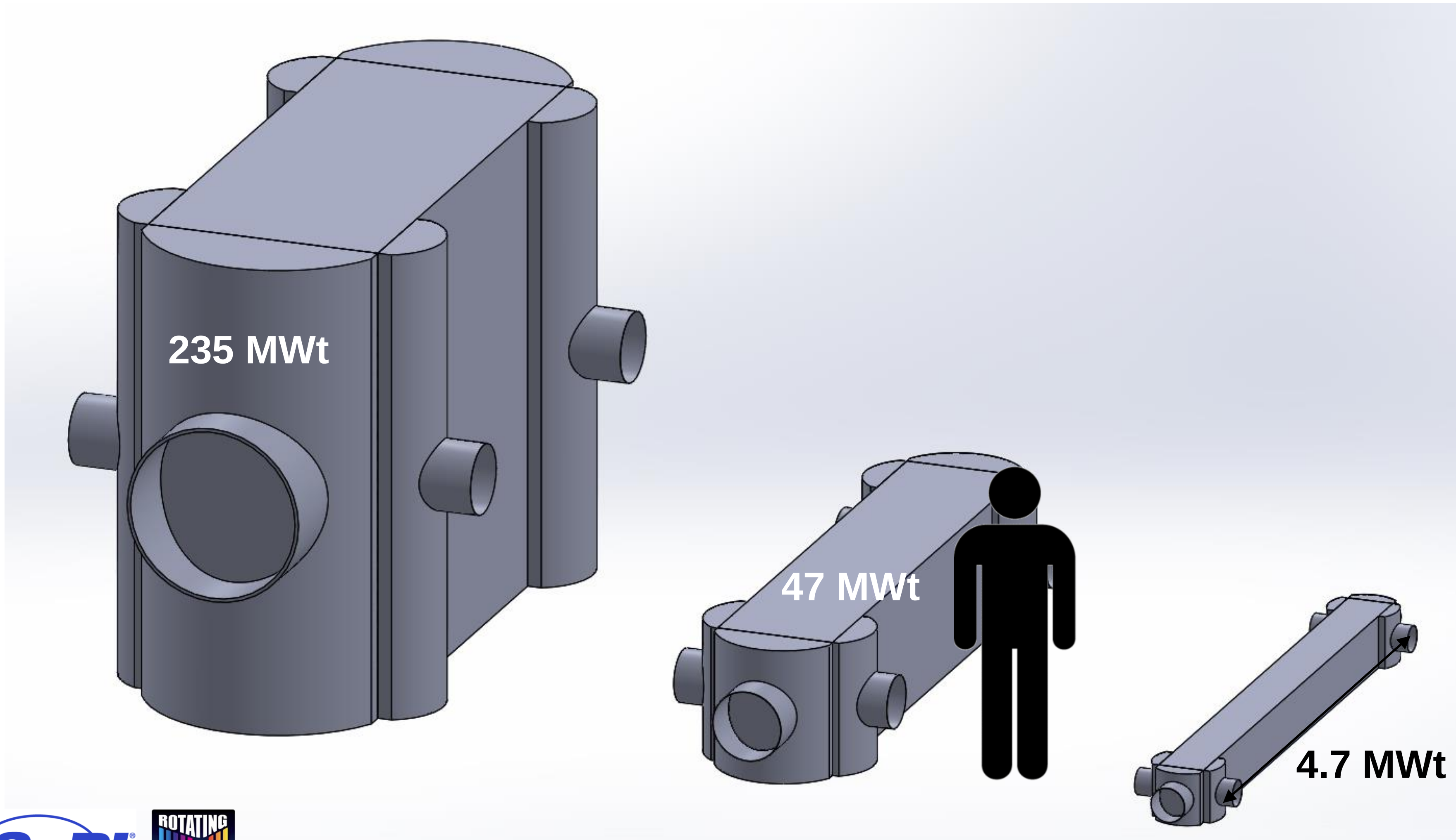
**Pressure containment:**

- High pressure loading and thermal growth
- Thickness between passages for containment

# Evaluation of thermal-mechanical stress to ASME Code



# Stacked-Sheet Recuperator – Size Comparison



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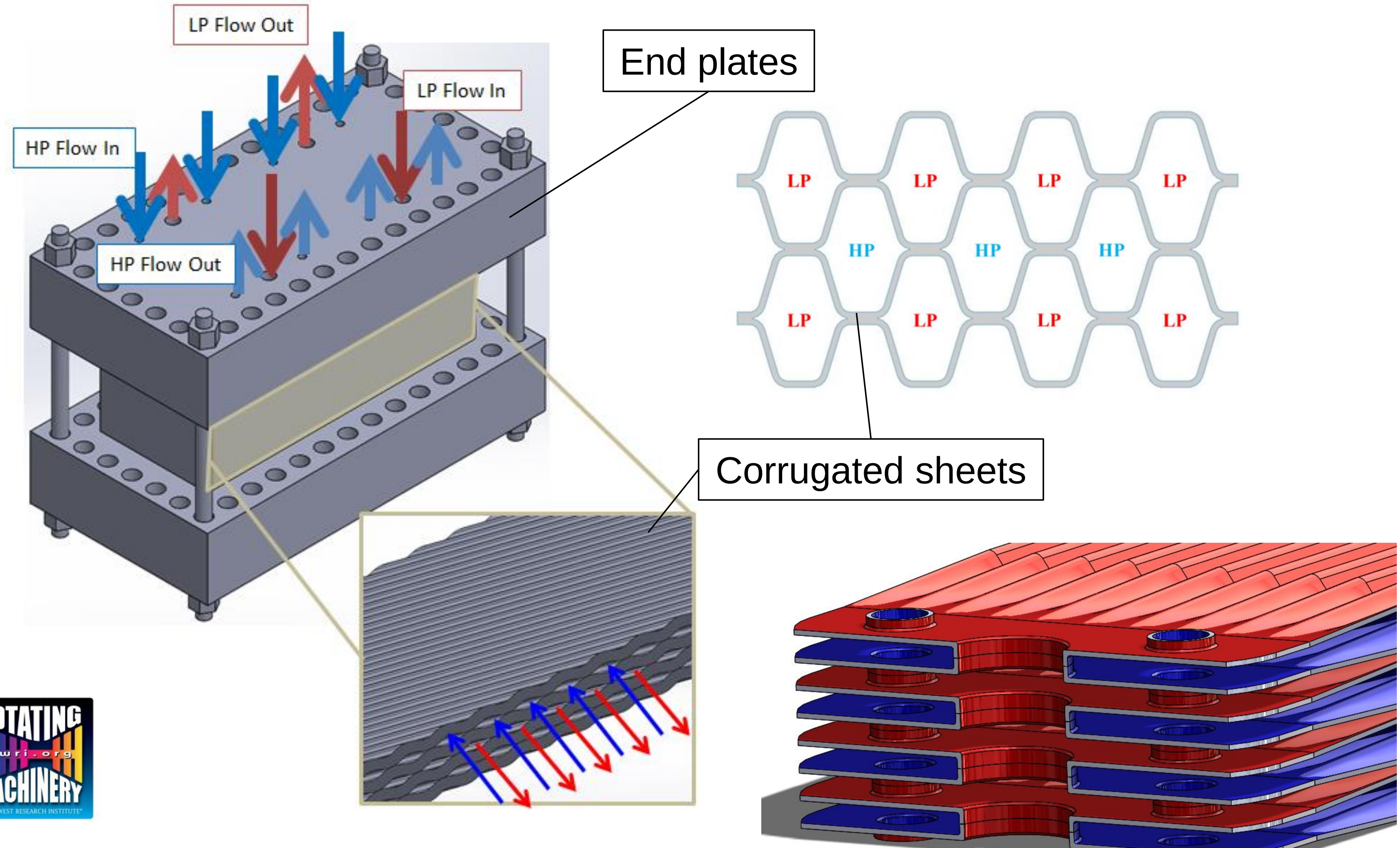
# The Corrugated Recuperator concept is similar to a plate-type heat exchanger with brazed channels



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# Corrugation size directly affects the overall sheet size and must provide pressure containment

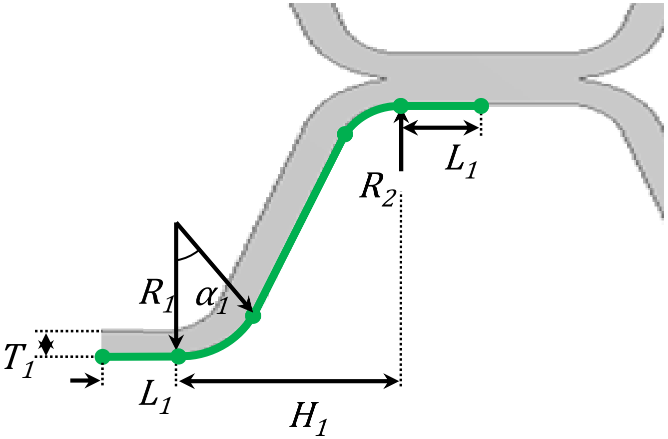
## Design Parameters

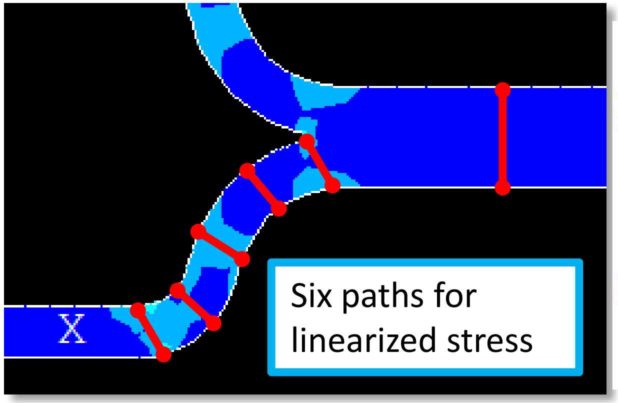
- Sheet width
- Corrugation size
- Sheet length
- Number of sheets
- Sheet thickness

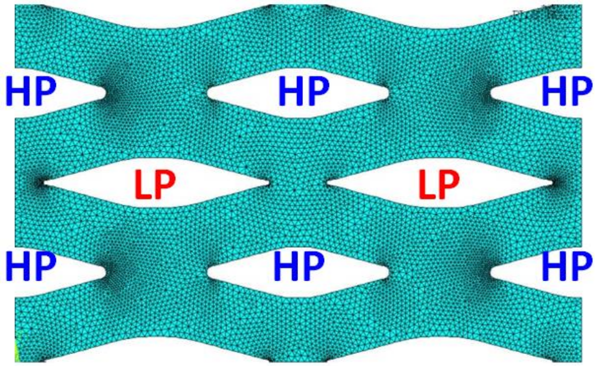
## Effects on Size and Cost

- Total height
- End plate thickness and cost

## Required sheet thickness for pressure containment is determined for a large range of corrugation design parameters



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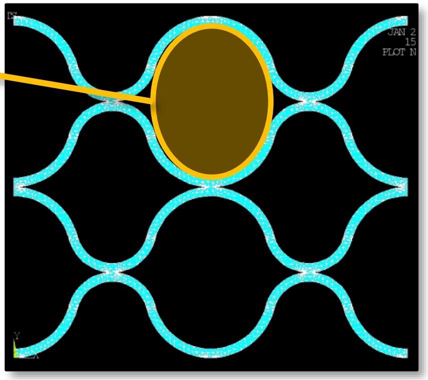
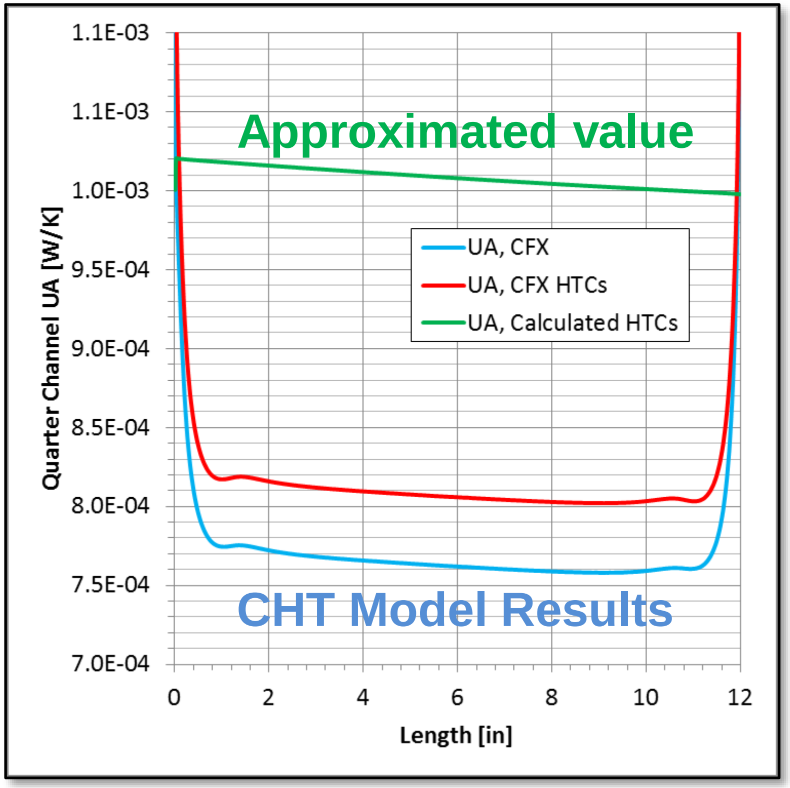
# CHT simulations were used to check the validity of passage size approximations for heat transfer

Elliptical flow passages assumed for HTC






A modification factor **~0.75** should be used for the approximate UA value

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# Additional analysis showed that the Corrugated Recuperator concept exceeds the cost criteria at the 47 MWt scale

- Manifolds had a higher than expected impact on the overall cost
- Cost of corrugated HX is above STEP target of $100/kW
  - ❖ Geometry for high risk manufacturing: $107/kW
  - ❖ Geometry for low risk manufacturing: $380/kW
- Since the concept does not meet the cost criteria, the recommendation is to discontinue further design or fabricate a prototype for testing.

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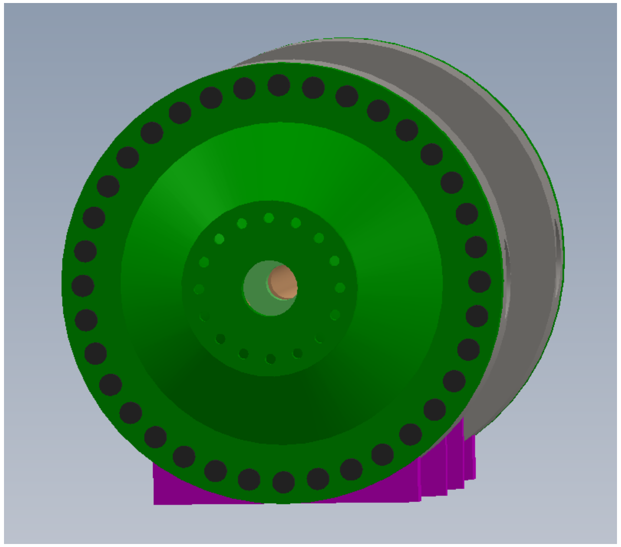
# Recuperator Concepts
# Engineering Analysis

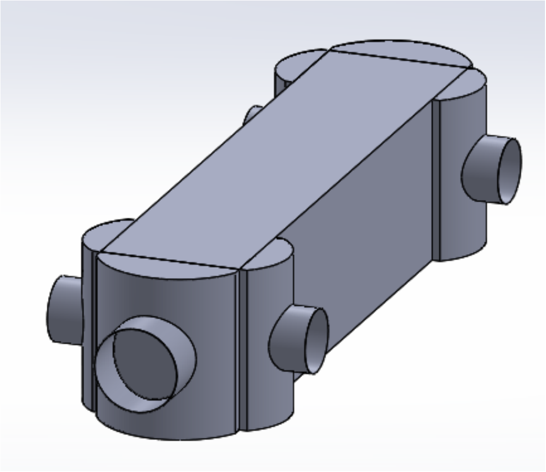
**46 MWt, 280 bar, 610°C, 97% Effectiveness, $\Delta P$ < 1.3 bar, <$100kW**

## Microtube



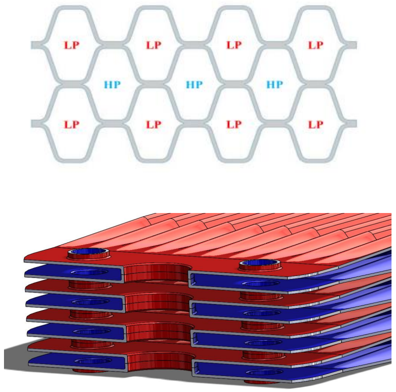
**$51/kWt** ✓

## Stacked-Sheet



**$47/kWt** ✓

## Corrugated




**> $107-380 /kWt**

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# Prototype Design, Fabrication and Testing

- Prototypes sized for performance testing in the Thar $sCO_2$ test loop, ~100 kWt
- Prototypes to encompass critical features of the 46 MWt scale recuperator
  - Manufacturing methods
  - Heat transfer assumptions

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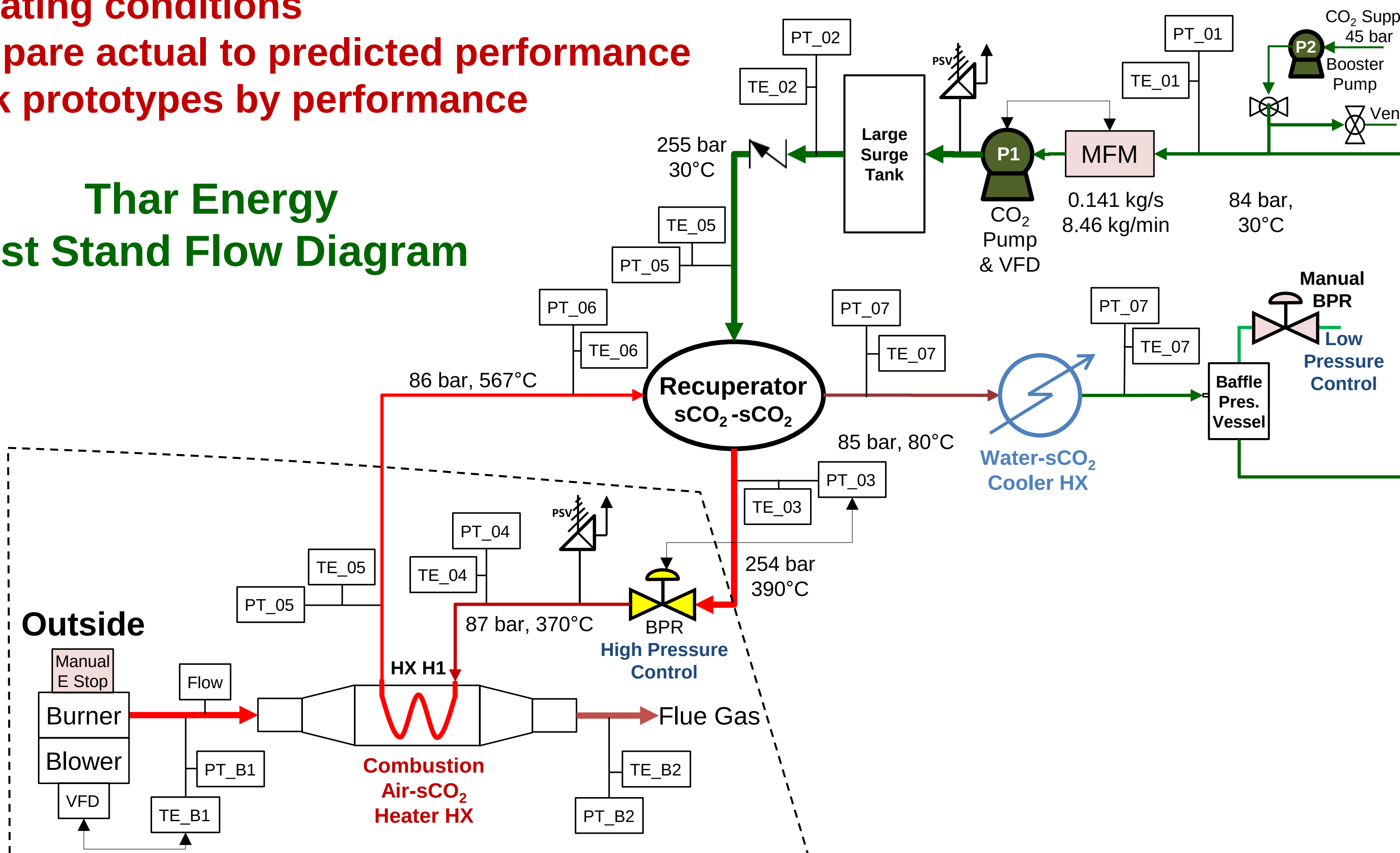
# Prototype HX Pressure and Performance Testing

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

## Thar Energy Test Stand Flow Diagram



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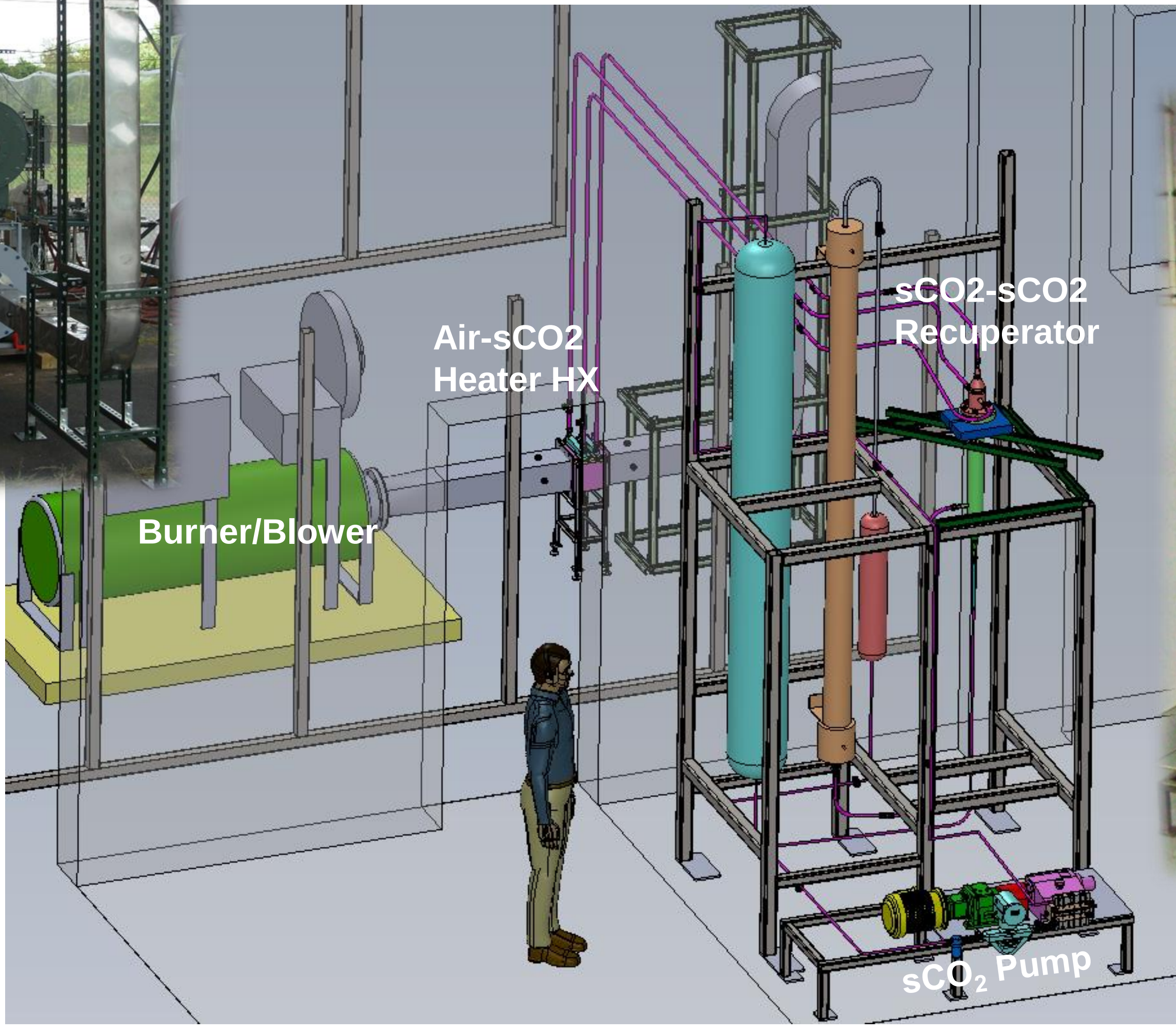
# HX Test Stand 3D Layout

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# Closing Summary

- Stacked Sheet and Microtube 46 MWt Recuperator Concepts meet STEP Performance and Cost Criteria.
- Both concepts 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.
- Recommending to discontinue work on the Corrugated Recuperator Concept since it does not meet the cost criteria.

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***Thank you for your kind attention***

**Questions?**

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Richard Dennis, Advanced Turbines Technology Manager
Seth Lawson, Program Officer, Advanced Energy Systems Division