

# Thar Energy

INTERSECTION OF ADVANCED MANUFACTURING AND CLEAN  
COAL AND CARBON CAPTURE TECHNOLOGIES

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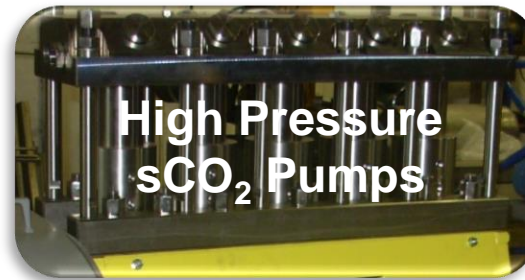
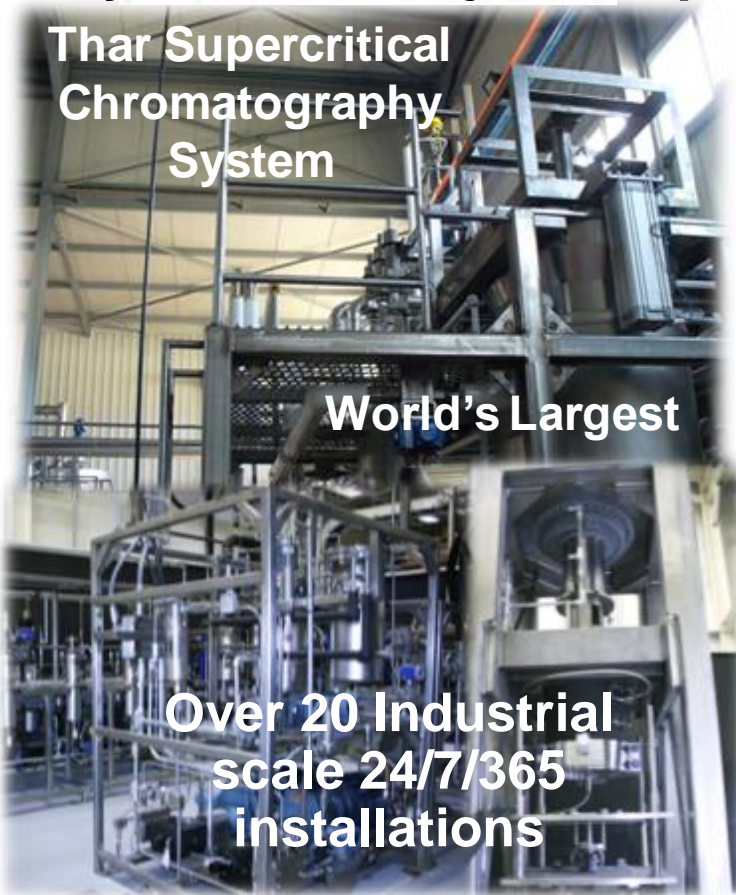
**April 30, 2019**

# Agenda

- Thar
  - 1. Background
  - 2. sCO<sub>2</sub> system
  - 3. Advance Manufacturing
  - 4. Questions

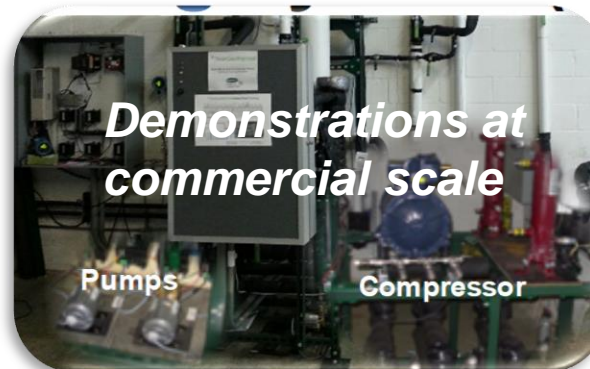
# The Thar Brand - Over 25 years of Innovation with “Green” Supercritical Fluid Technologies

**Design and commercialization of supercritical systems & major components**



**Over 5,000 scientific instruments installed**

**Direct Exchange, R744 (CO<sub>2</sub>) Geothermal Heating & Cooling**



# Thar has a history of successfully designing & commercializing Green Products using recycled Carbon Dioxide.

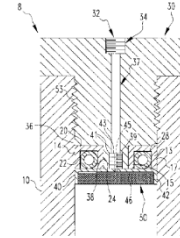
Launch  
Suprex



Suprex sold to  
Teledyne Isco  
Launch  
Thar Brand



Pressurized  
Vessel with Self-  
Energizing Seal



CO<sub>2</sub>



Spin out  
operating  
divisions

1982



Chemical  
Engineering

1985

Earn  
PhD

U.S. Patents 4,814,089 & 4,871,453  
Chromatographic Separation  
Method and Associated Apparatus

1990

Launch Operating Div.

- Thar Instruments
- Thar Process
- Thar Pharma

Products and Processes  
Commercialized

Awards & Patents Received  
U.S. Patents #5,336,869, #5,461,648,  
#5,694,973, #5,850,934, #5,879,081,  
#5,886,293, #6,908,557, #7,091,366,  
#6,698,214. ....

2007

Acquired  
Berger  
from  
Metler  
Toledo

2001, 2002 Governor's Export Excellence Award Finalist  
2002 National Small Business Exporter of the Year  
2002 NIST ATP Awardee (Microrefrigeration)  
2002, 2003 Top 25 Biotech Companies  
2002, 2003 Top 100 Fastest Growing Companies  
2003 Fastest Growing Small Manufacturer Award  
2004 Manufacturer of the Year



# Thar Timeline (cont.)

**NIST funds micro-refrigeration project**

**2002**

**2005**

**2009**

**2010**

**2012**

**2014**

Thar Instruments, ~125 strong, Offices worldwide, Sold to **Waters** THE SCIENCE OF WHAT'S POSSIBLE®

1st **R744 Geothermal Cooling Demonstration**

Validated potential for R744 DX heat pump cycle

**Launch TharGeothermal**

Laboratory testing and component development

**Air Side HX**

**High Pressure sCO<sub>2</sub> Pumps**

**Advanced Heat Exchanger Technology Demonstration**

Demonstrations at commercial scale - **geothermal heating & cooling system (15-20 ton)**



**2002**

**2005**

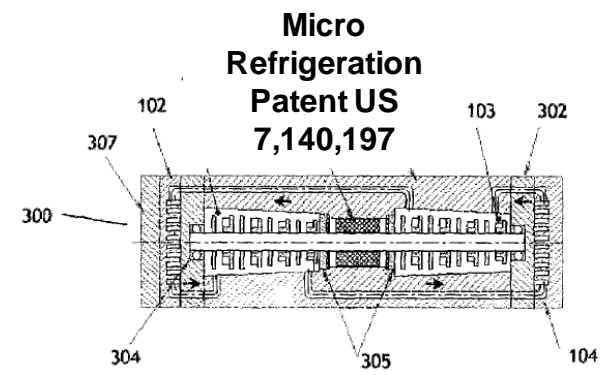
**2009**

**2010**

**2012**

**Radiant Floor**

**2014**

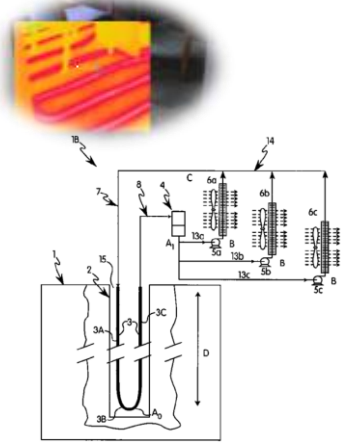


**Evaluation of Commercial Drill Technology**



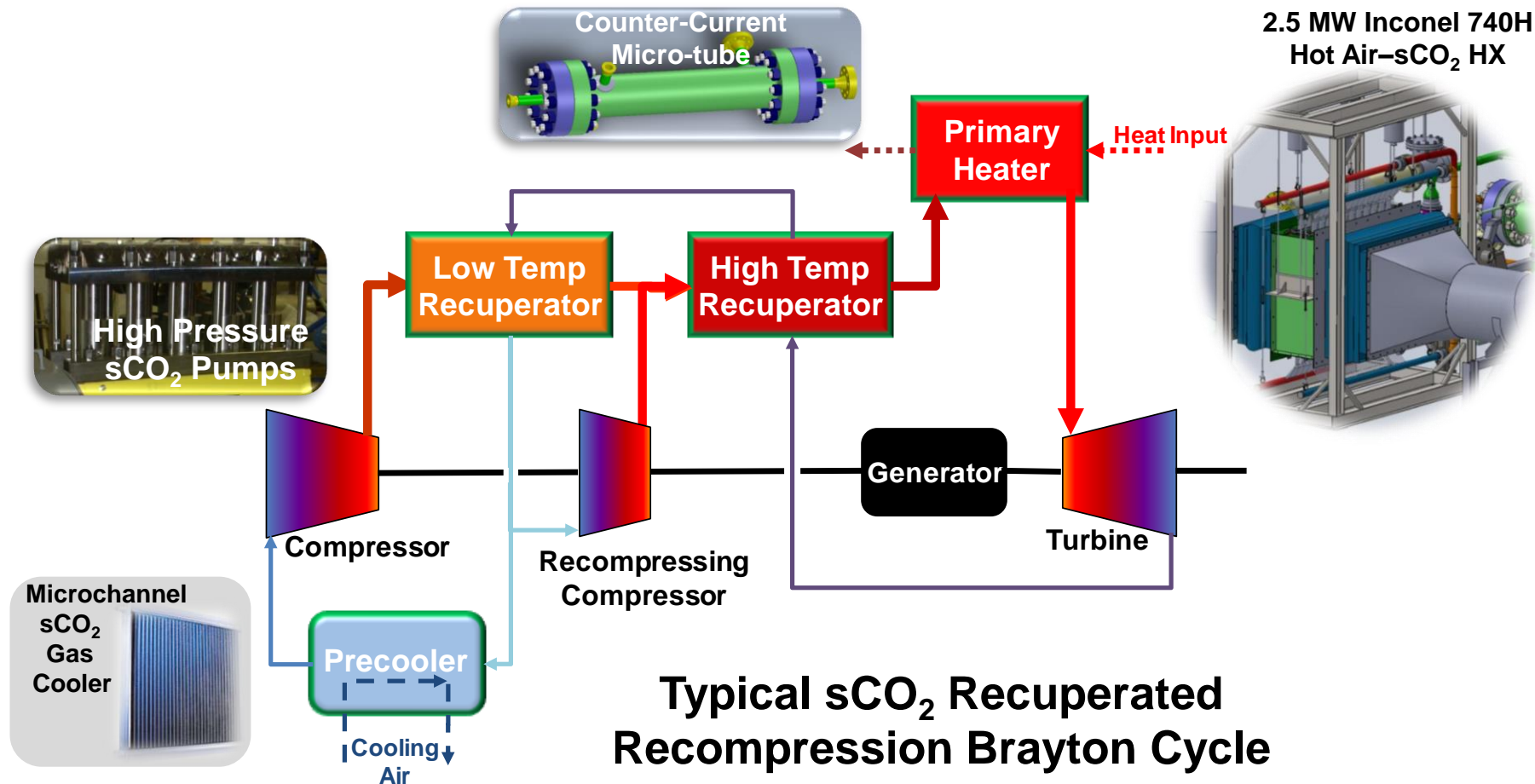
**Vertical and Horizontal well fields installed**

**Geothermal Energy System Patent US 8,468,845**



Heat Exchangers are key to improving sCO<sub>2</sub> power cycle efficiency and costs

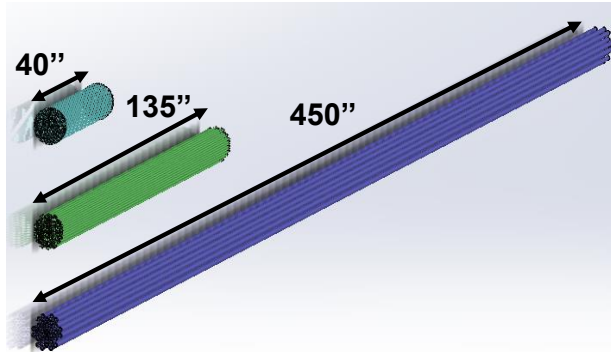
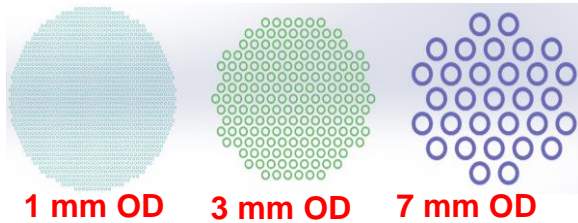
## Thar Energy sCO<sub>2</sub> Recuperators, Heater HXs & Precooler HXs



Typical sCO<sub>2</sub> Recuperated  
Recompression Brayton Cycle

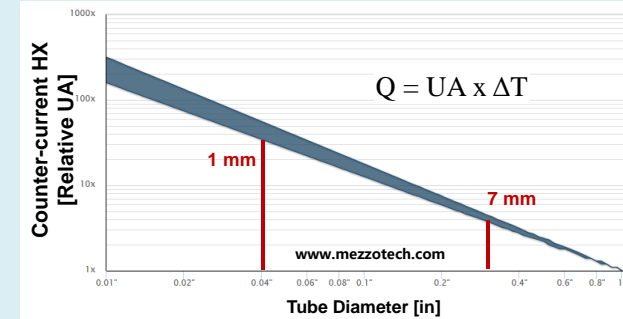
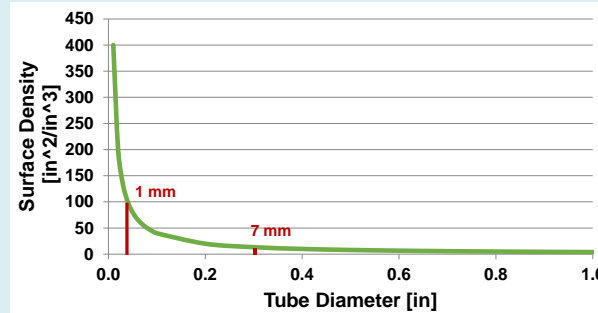
# Microtube Heat Exchanger Advantages

**Counter-current**  
sCO<sub>2</sub> to sCO<sub>2</sub>  
Same capacity, effectiveness  
& pressure drop



	1mm	3mm	7mm
Tube Length	40"	135"	450"
Tube Number	1500	175	30
Bundle Weight	17 lb	59 lb	244 lb
Surface Density	76 in <sup>2</sup> /in <sup>3</sup>	30 in <sup>2</sup> /in <sup>3</sup>	12 in <sup>2</sup> /in <sup>3</sup>
Efficiency	97%	97%	97%

**Smaller diameter tubing improves  
Surface Density & Heat Transfer Coefficient**



*Design Flexibility*

*Higher Performance*

*Compact, Smaller Footprint*

*Lighter Weight*

*Optimized Material Use*

## 3D Printed Heat Exchanger

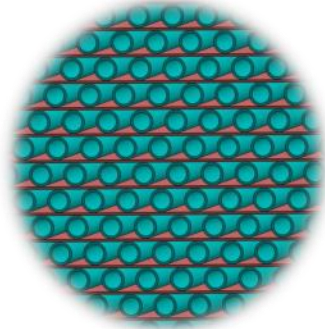
- **Earliest 3D Printed Heat Exchanger ever Built**
  - Built in 2012
  - Inconel 617
  - Patented Manifold Design
  - Very compact
  - Tested at KAPL
  - **Expensive: \$28,000**



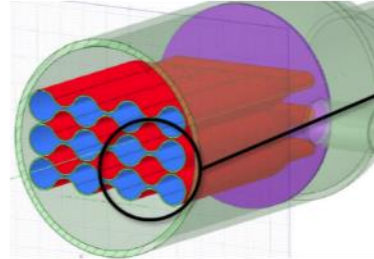


# Recuperator Concepts Selected from Brain Storming

Microtube



Corrugated



Helical

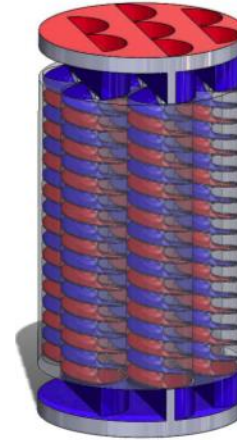
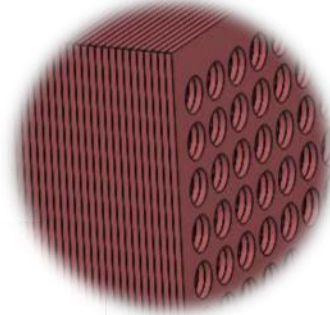


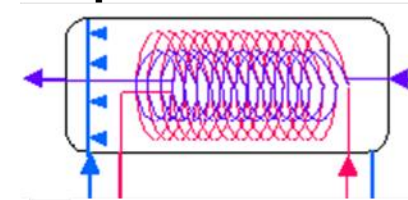
Plate-Fin



Stacked-Sheet



Spiral-Wound



Liquid Metal Bath

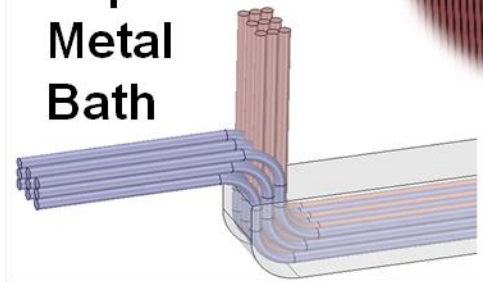
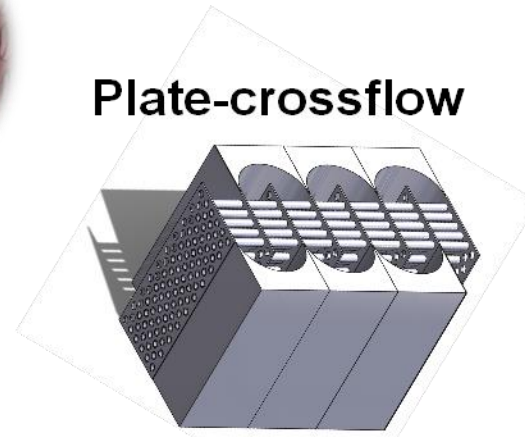
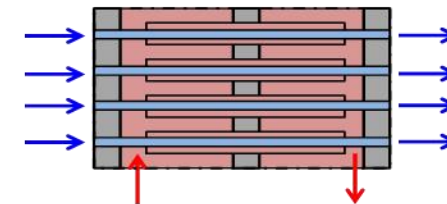


Plate-crossflow



Double-pipe

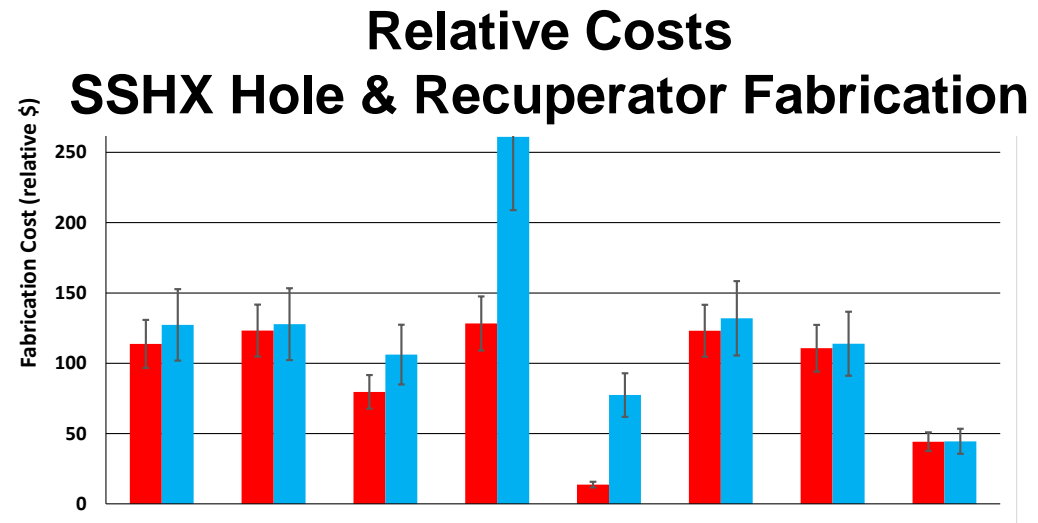


## SSHX Manufacturing Options

### Extensive discussions with Vendors

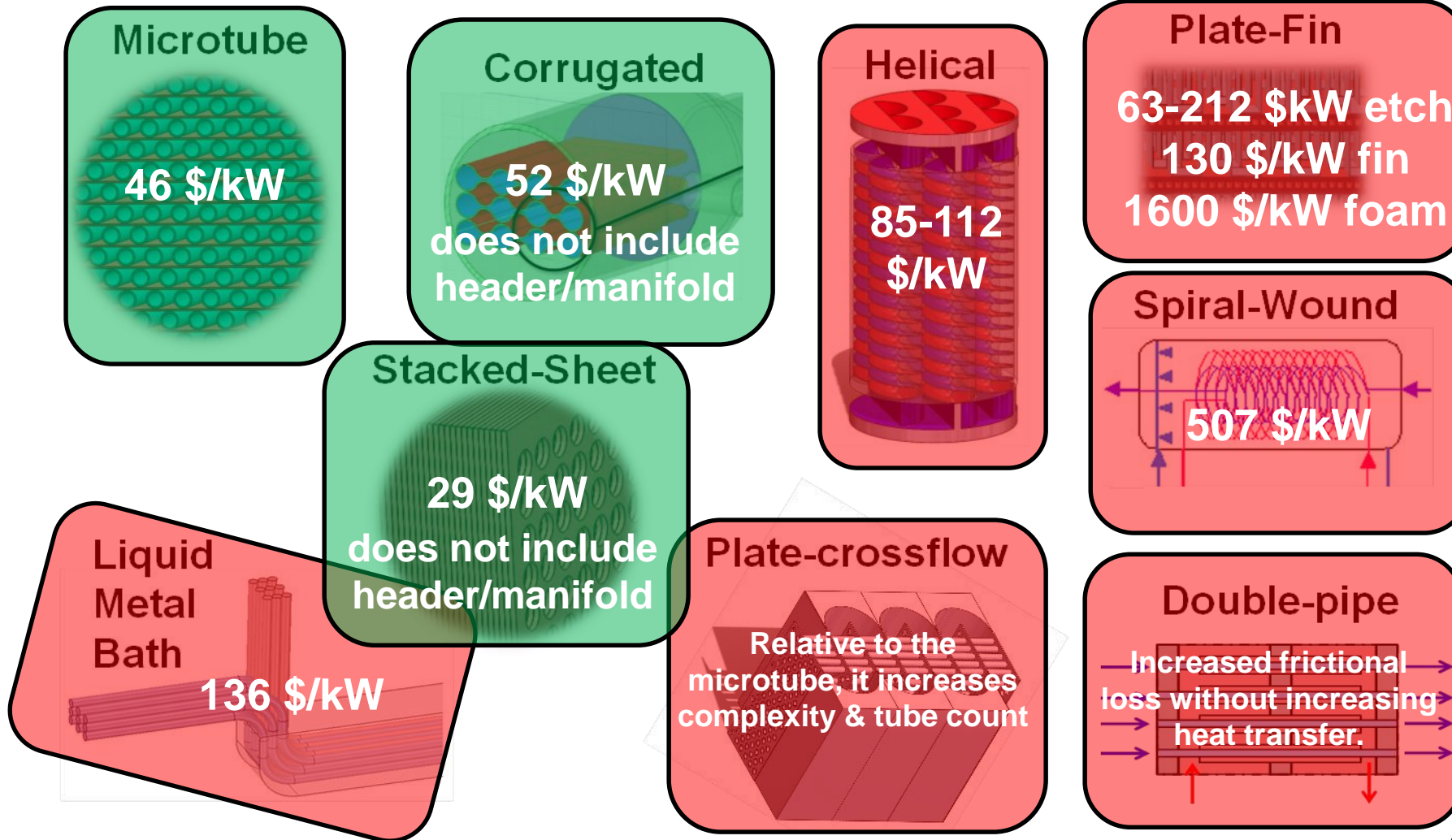
### *Subtractive vs. Additive Manufacturing*

- 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%**)



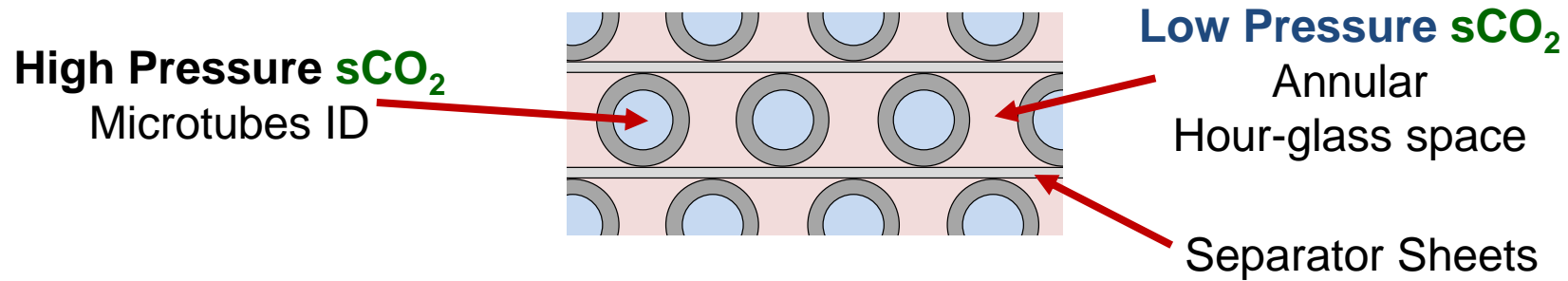
# The Microtube, Corrugated & Stacked-Sheet Recuperator Concepts were *down selected* for low complexity and cost

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

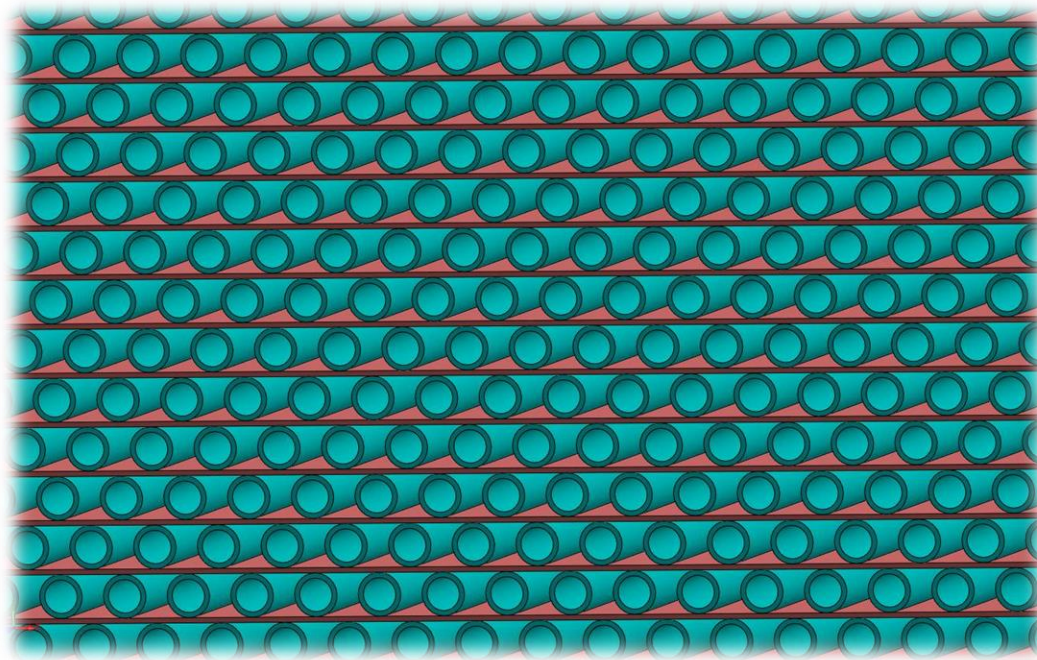




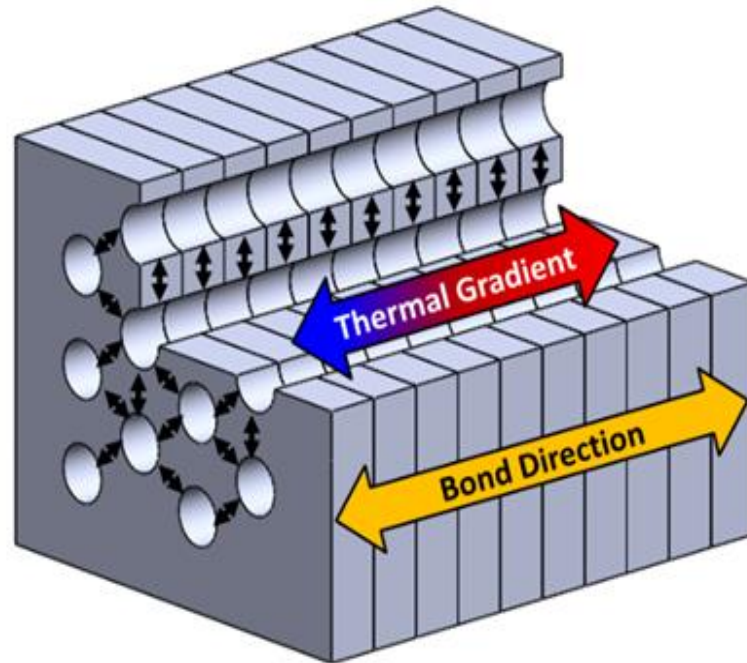
## Thar Recuperator Tube Bundle



**Tube Bundle**  
**4,500 m<sup>2</sup>/m<sup>3</sup>**

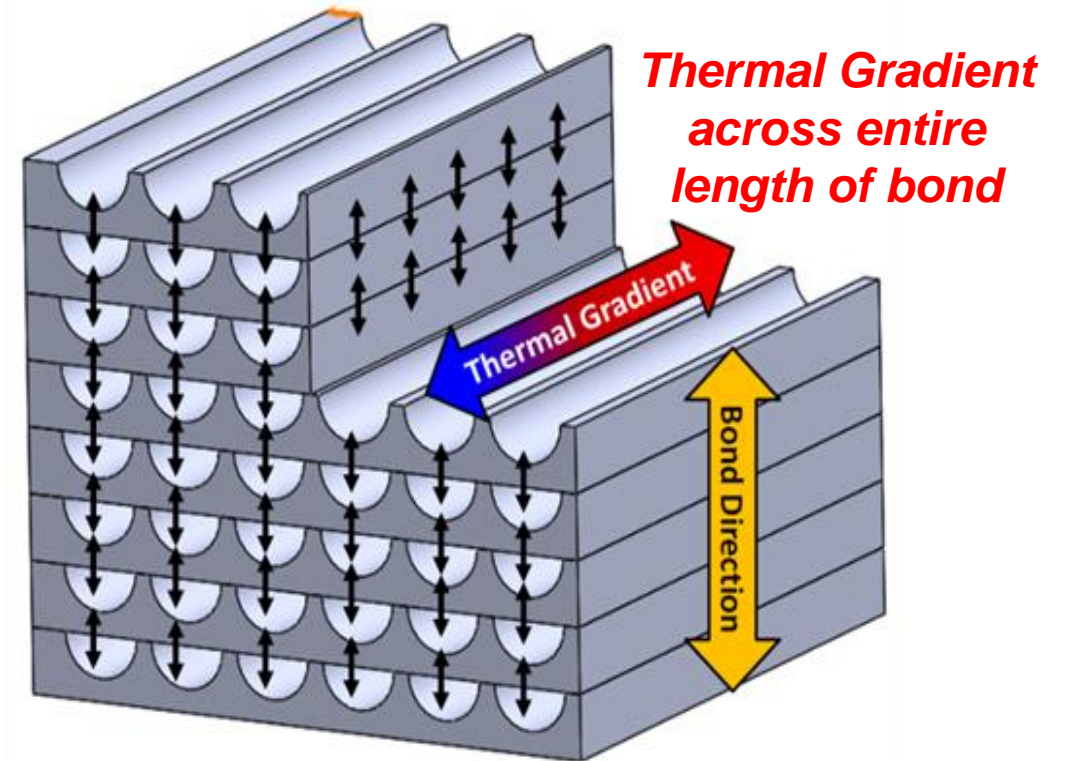


## SSHX and Printed-Circuit HX Mechanical & Thermal Stress Analysis



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

**Improves structural integrity and thermal compliance**



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

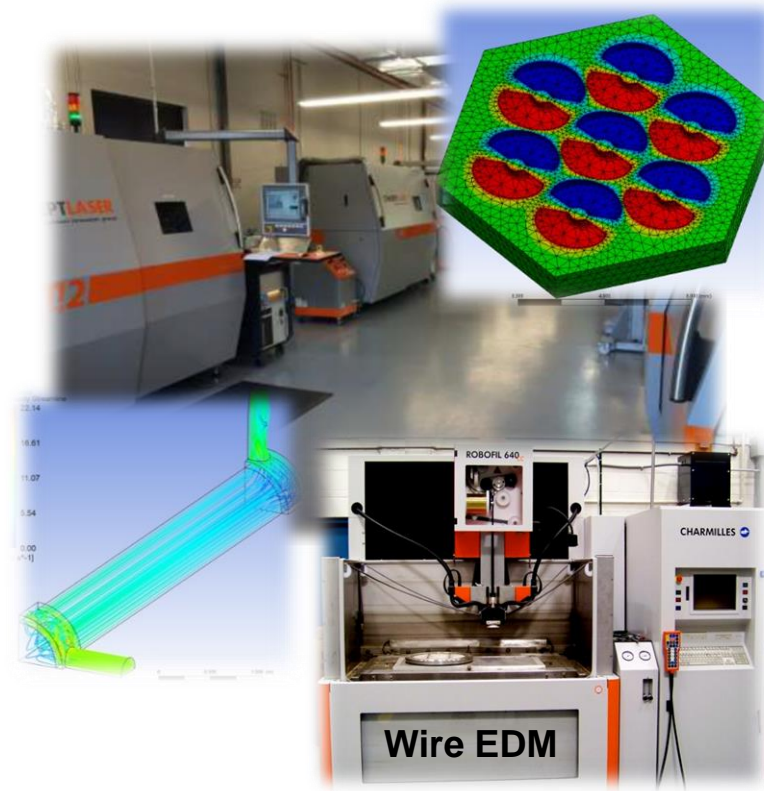


## HTR Recuperator Concepts Engineering Analysis & Down Select

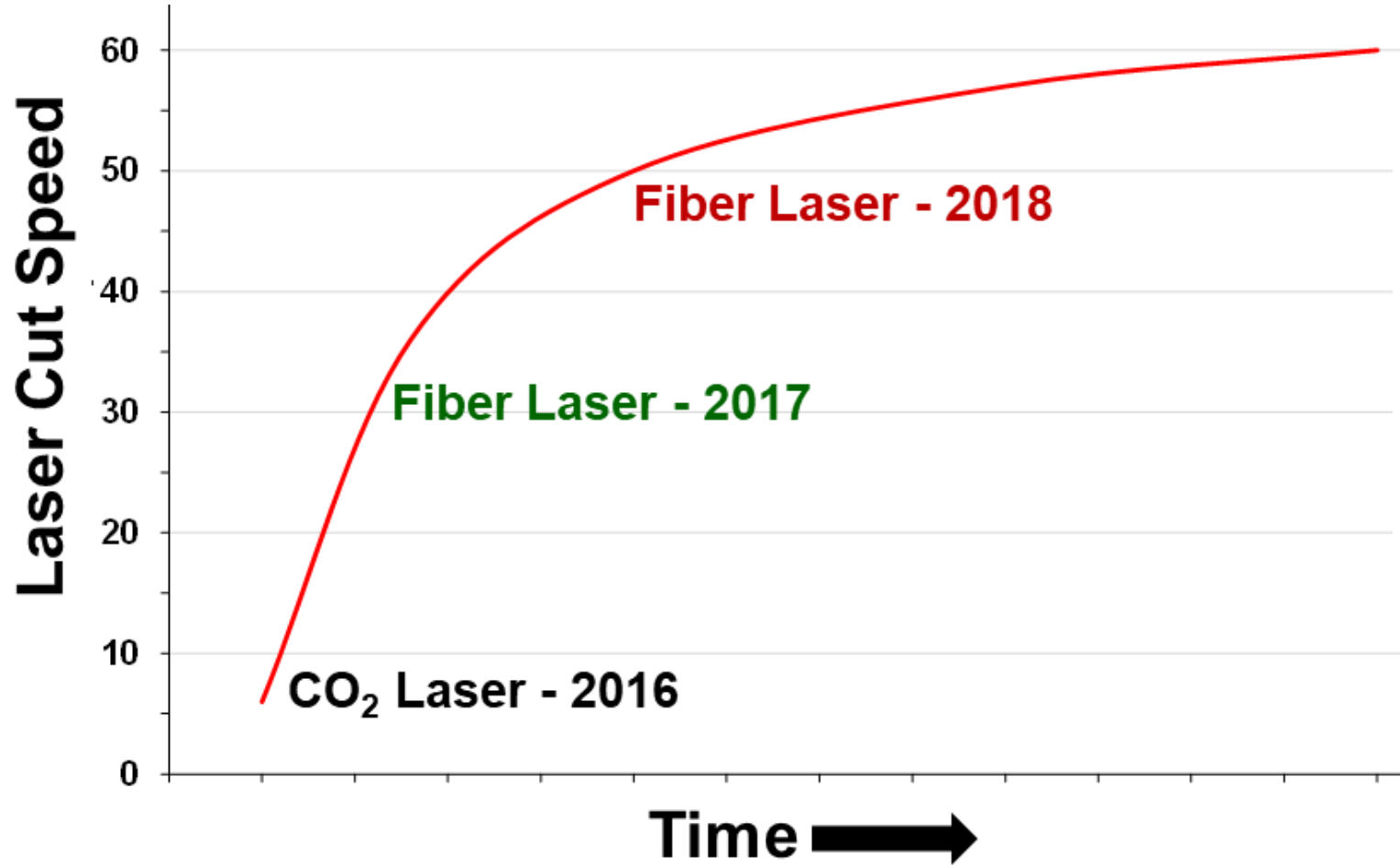
- Thermal-Hydraulic performance modeling and analysis
- Advanced manufacturing methods and tolerance
- Fabrication cost analysis

### *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

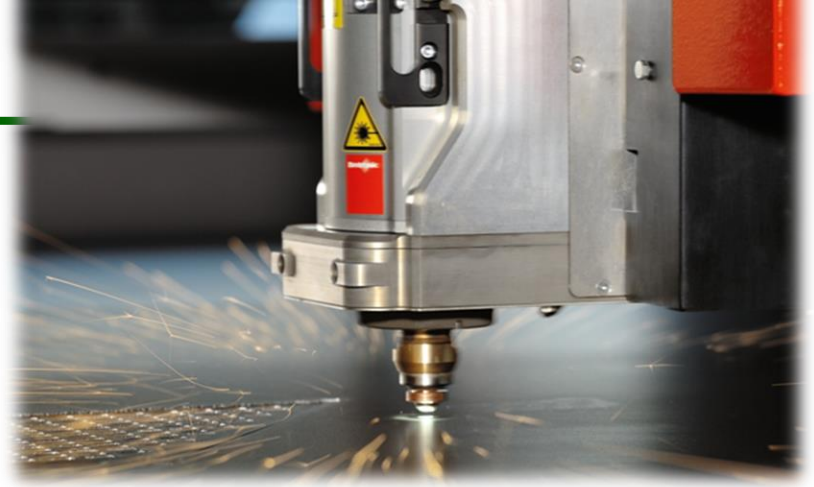
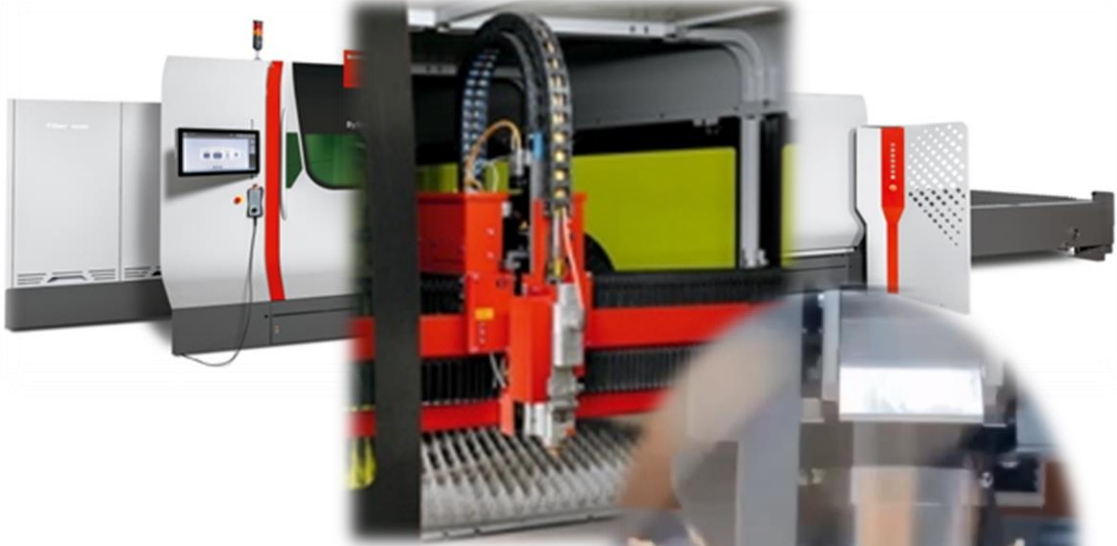


## Advances in Manufacturing Technology



### Digital Revolution:

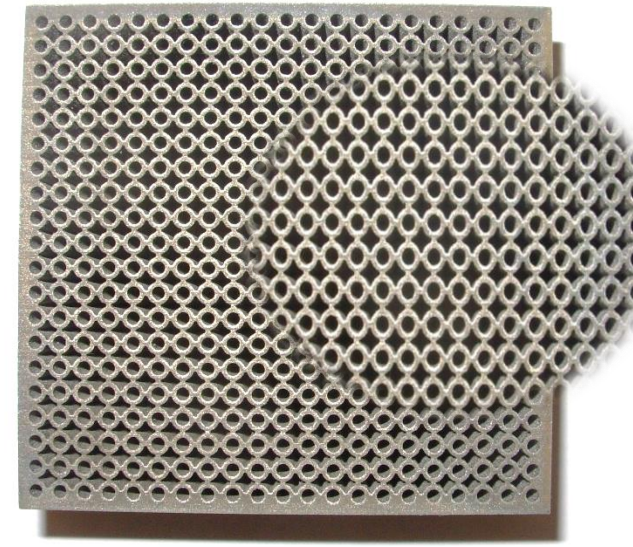
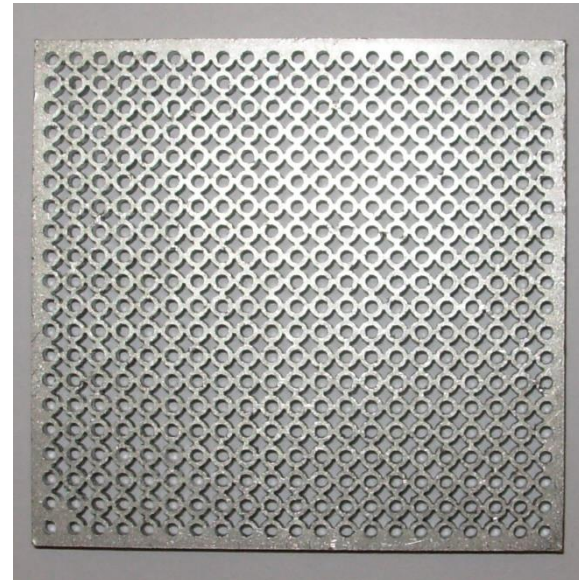
- Optimizes Power Consumption
- Provides for Peak Power
- Cut any shape
- Fiber Laser Cutting
- EDM
- Water-jet Cutting
- ECM



3D Printed circle-star pattern can be *laser cut*

Laser cut

3D Printed



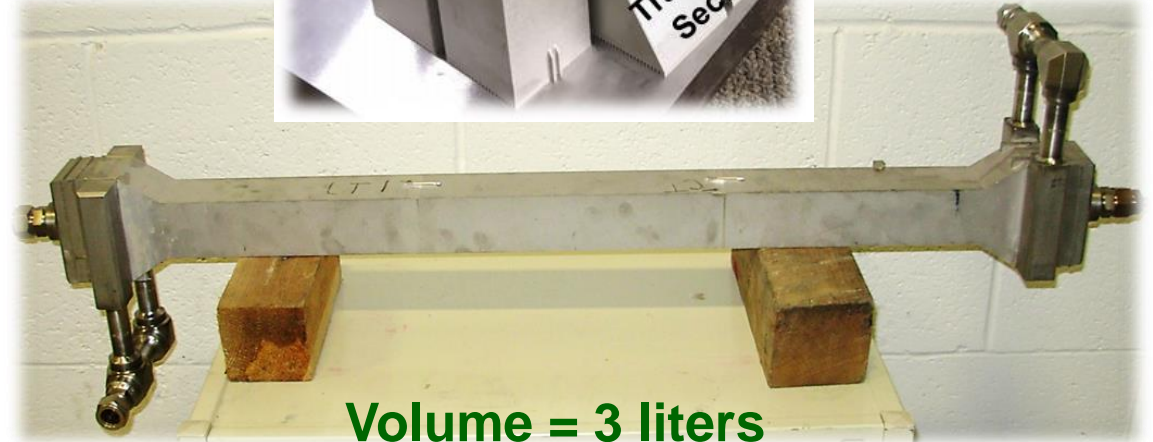


## Stacked-Sheet Recuperator Prototypes

### Laser-SSHX



### 3D-SSHX



**Volume = 3 liters**

***6 times more compact***

# Prototype 3D-SSHX Recuperator

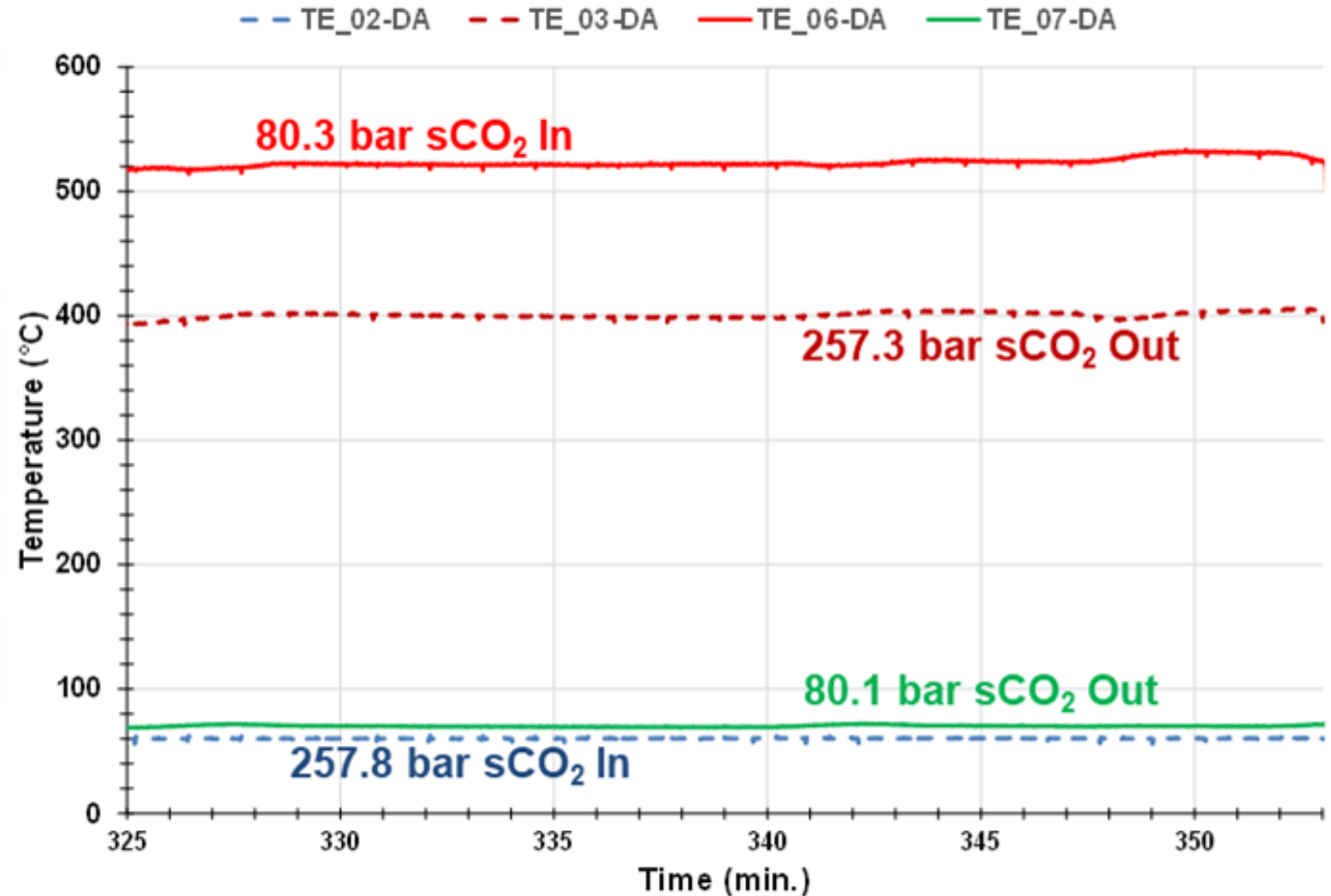
## Test Loop Steady State Time vs. Temperature Plot



Mounted in test loop before final insulation installed



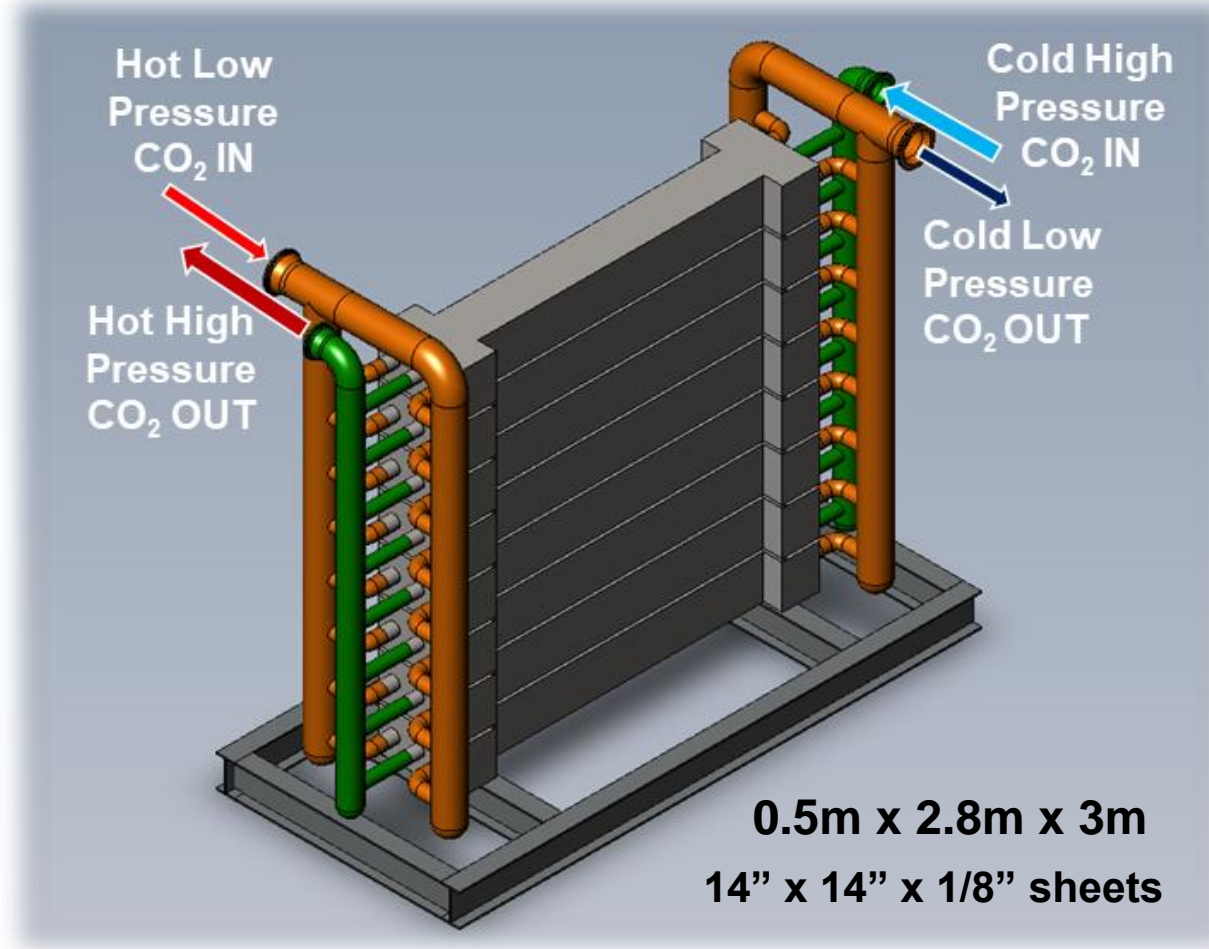
Thermal IR image during commissioning





## 46 MWt Laser-SSHX Recuperator

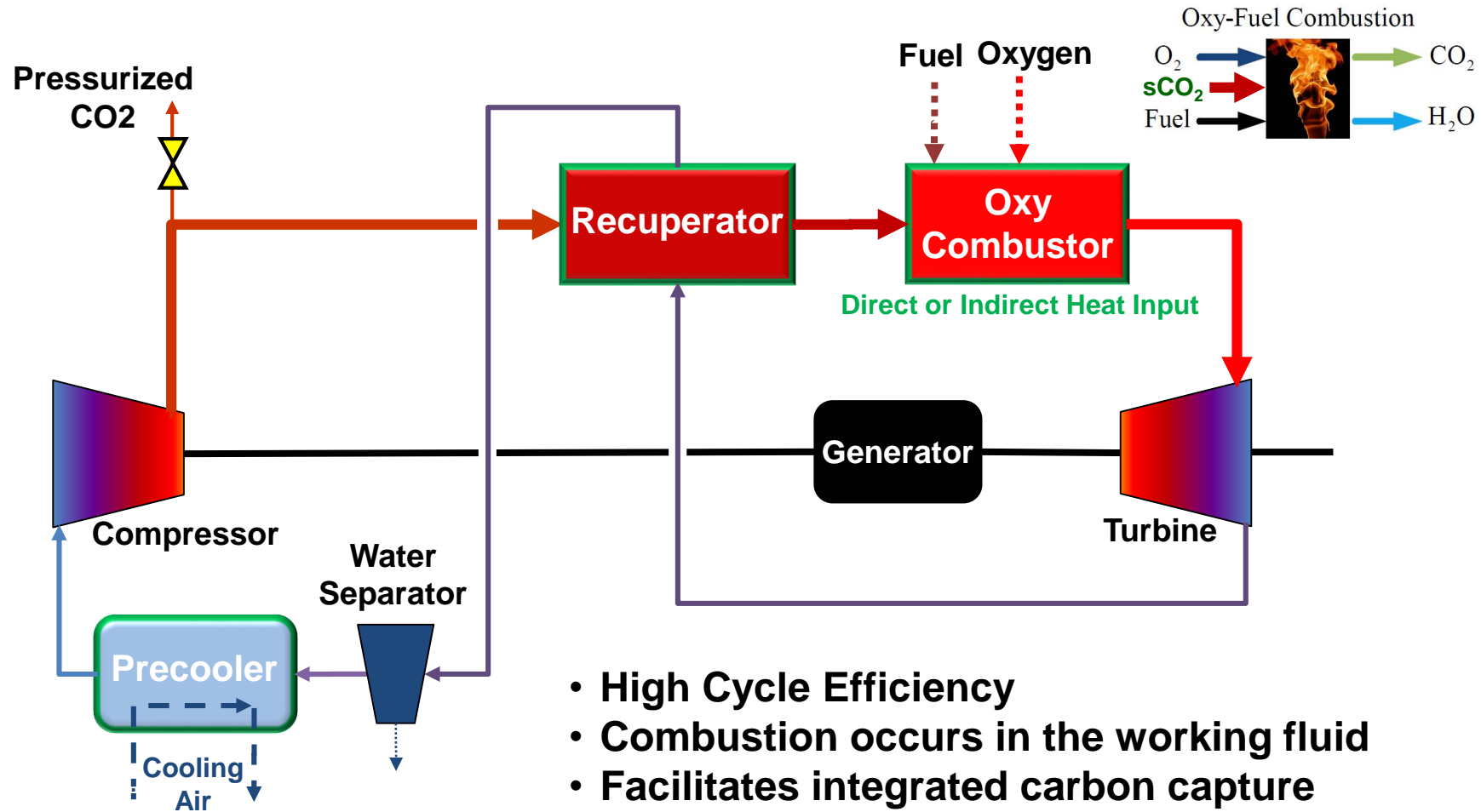
**Example: Eight stacked Laser-SSHX sub-modules**



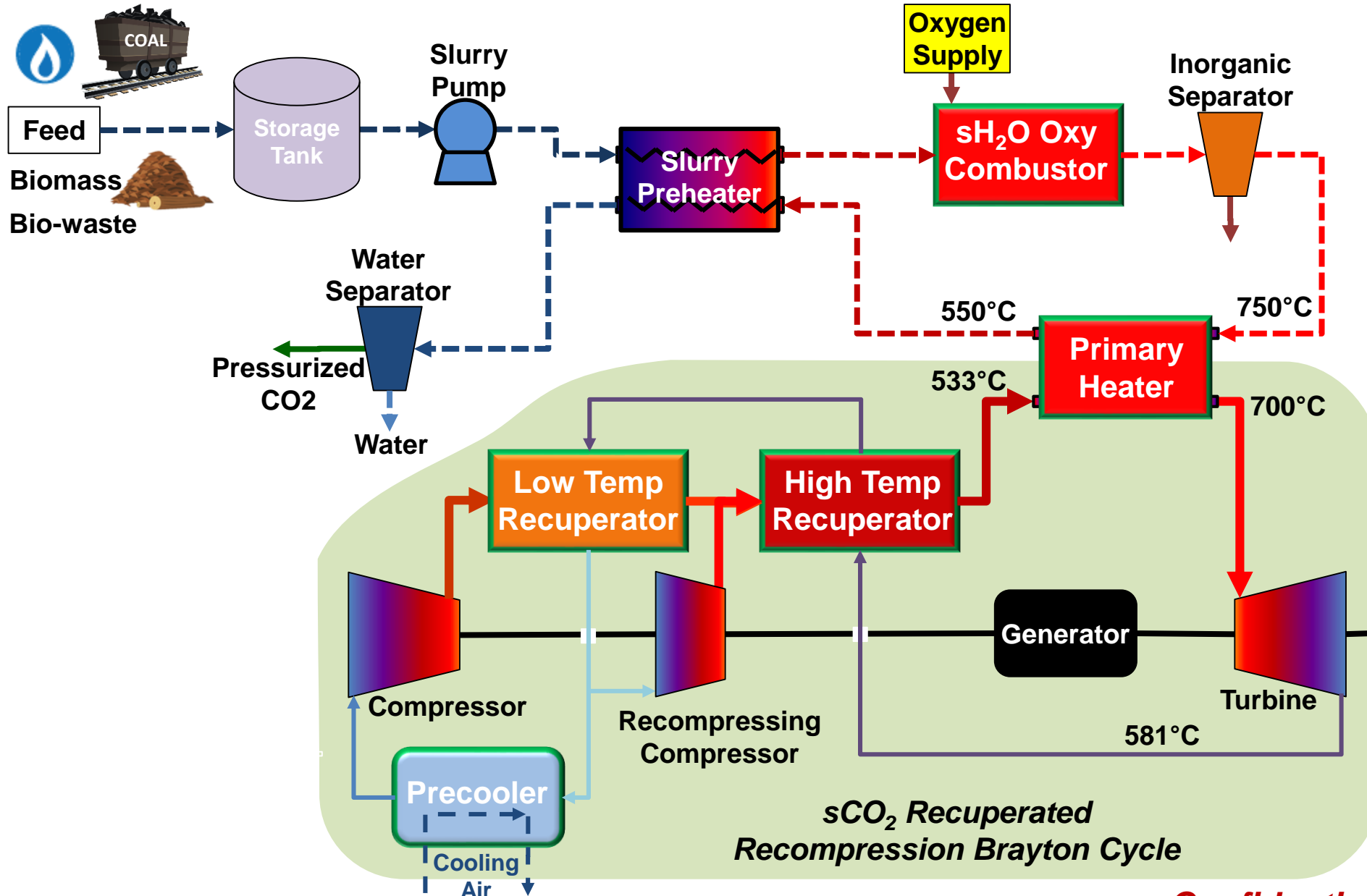
**3D-SSHX**  
**57% volume**  
**decrease**

**Conservative circle-circle pattern design - March 2018**

## Direct sCO<sub>2</sub> Oxy Combustion Cycle

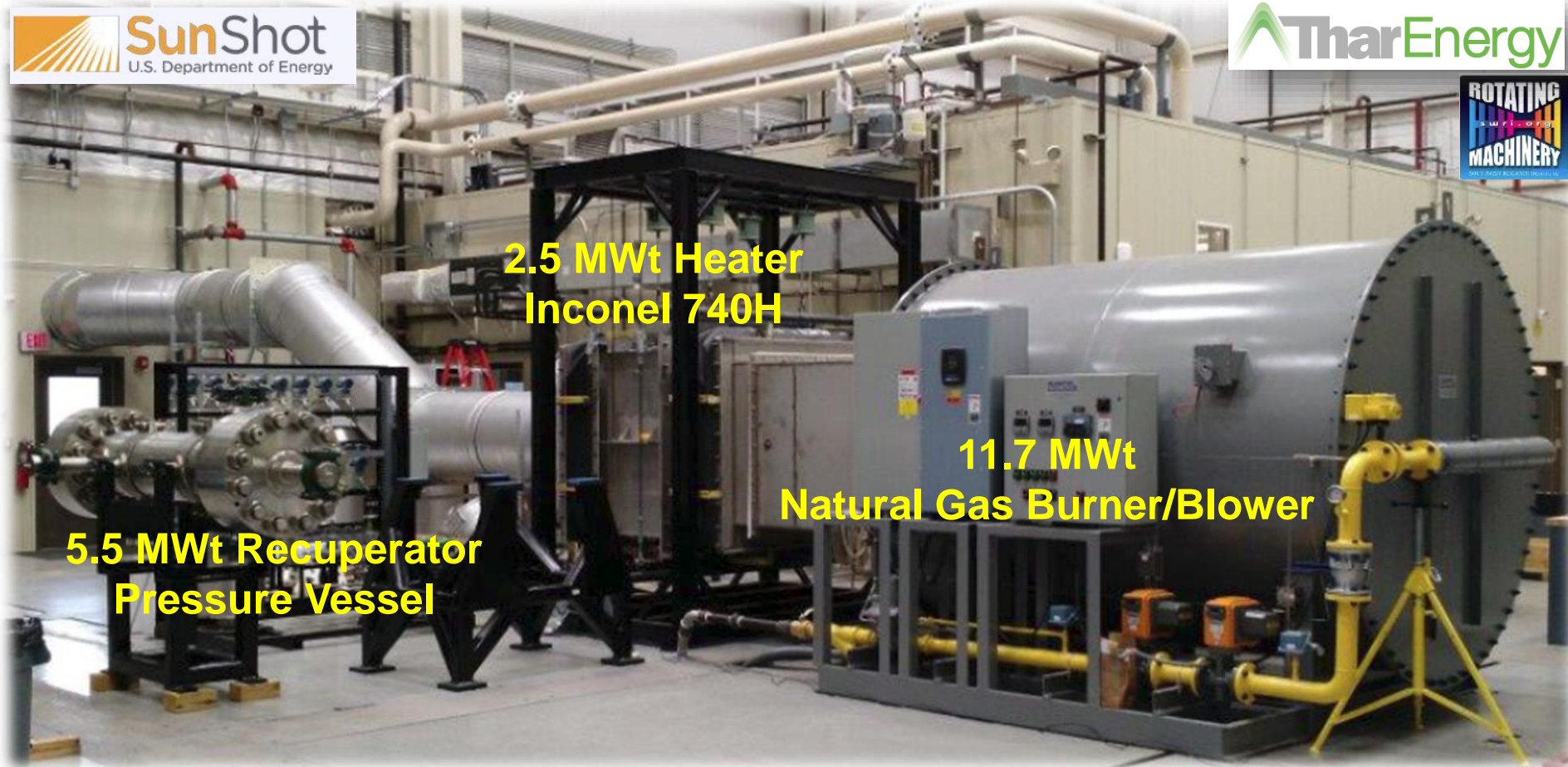


- High Cycle Efficiency
- Combustion occurs in the working fluid
- Facilitates integrated carbon capture
- Water separation
- Compatible with dry cooling techniques



# Installed at SwRI

## Thar Energy's *sCO<sub>2</sub>* Primary Heater





## Oxy Combustion Test Stand at Thar





## Questions and Discussions!!!

- Thank You

Our 75,000 Sq. Ft Facility in Pittsburgh



**Lalit Chordia, Ph.D**  
**Thar**  
**150 Gamma Drive**  
**Pittsburgh, PA 15238**

## What Drives Distributed sCO<sub>2</sub> Power Systems

- Cost
  - Smaller Package enables it to be factory made
    - HX, expanders and pumps are smaller
    - A 5 MW system can fit into a 40 foot container
  - Smaller Package allows for easy installation
- Fuel Flexibility
  - Natural Gas, and Coal
  - Waste Products
    - Food waste, Manure, Sewage solids, etc.
- Zero Emissions: Oxy-combustion
- Air Cooled: No water requirement
- Looks and feel like a diesel genset