2015 University Turbine Systems Research Workshop

Atlanta, Georgia

November 3, 2015

Thar Energy Manufacturer of Heat Exchangers for sCO_2 Power Cycles

Lalit Chordia, PhD

TharEnergy

150 Gamma Drive

Pittsburgh, PA 15238

www.tharenergyllc.com

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Pittsburgh, PA 15238
www.tharenergyllc.com

Outline

- Introduction
- Thar Energy Projects
- Modular Recuperator Project

TharEnergy

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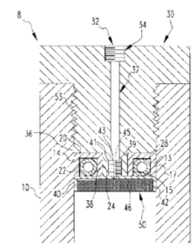
Thar has a history of successfully designing & commercializing Green Products using recycled Carbon Dioxide.

Launch Suprex

Suprex sold to Teledyne Isco

Launch Thar Brand

Pressurized Vessel with Self-Energizing Seal



ThartProcess

Thar Instruments

Spin out operating divisions

1982

Carnegie Mellon University

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

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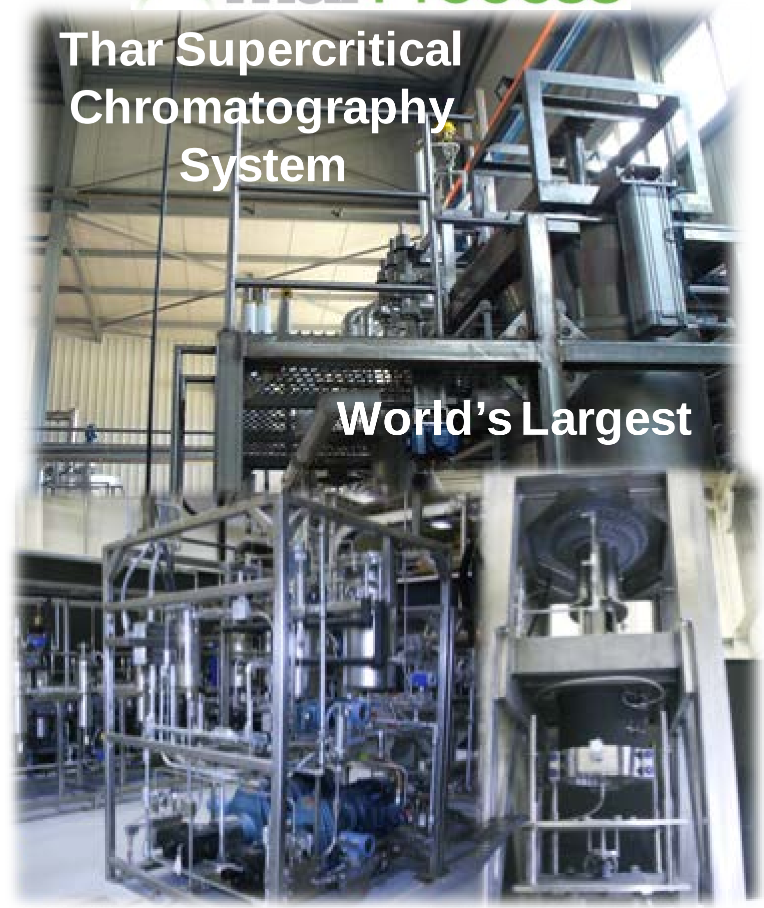
Over 5,000 green installations world wide

ThairProcess



Over 20 Industrial green installations world wide

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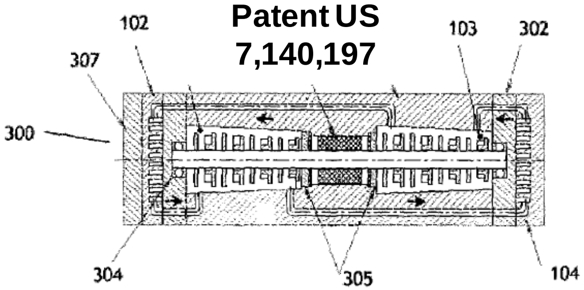
Thar Timeline (cont.)

NIST funds micro-refrigeration project

2002

2005

Micro Refrigeration Patent US 7,140,197



1st R744 Geothermal Cooling Demonstration

Validated potential for R744 DX heat pump cycle

2009

Thar Instruments, ~125 strong, Offices worldwide, Sold to Waters

Waters THE SCIENCE OF WHAT'S POSSIBLE.

2010

Launch TharGeothermal

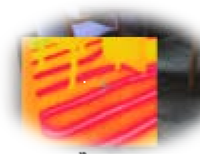
Evaluation of Commercial Drill Technology

Laboratory testing and component development

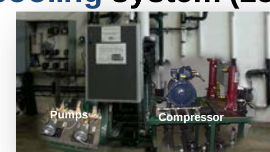
2012

Vertical and Horizontal well fields installed

Radiant Floor



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

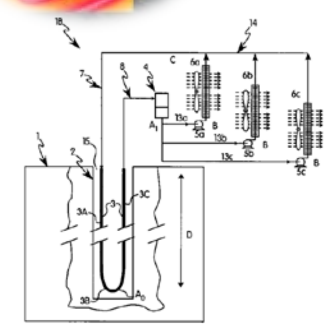


High Pressure sCO_2 Pumps

Advanced Heat Exchanger Technology Demonstration

2014

Geothermal Energy System Patent US 8,468,845



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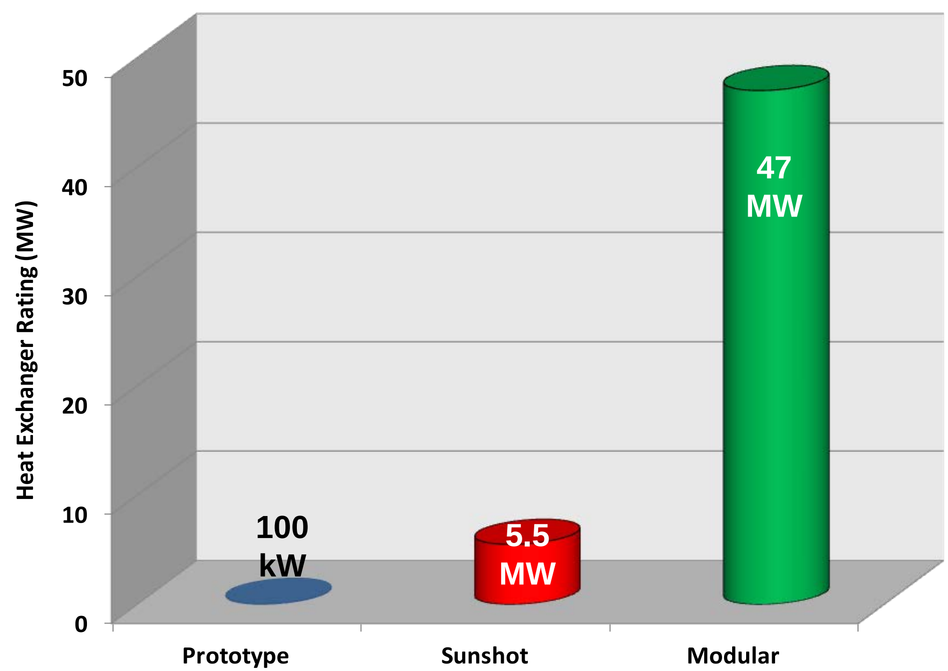
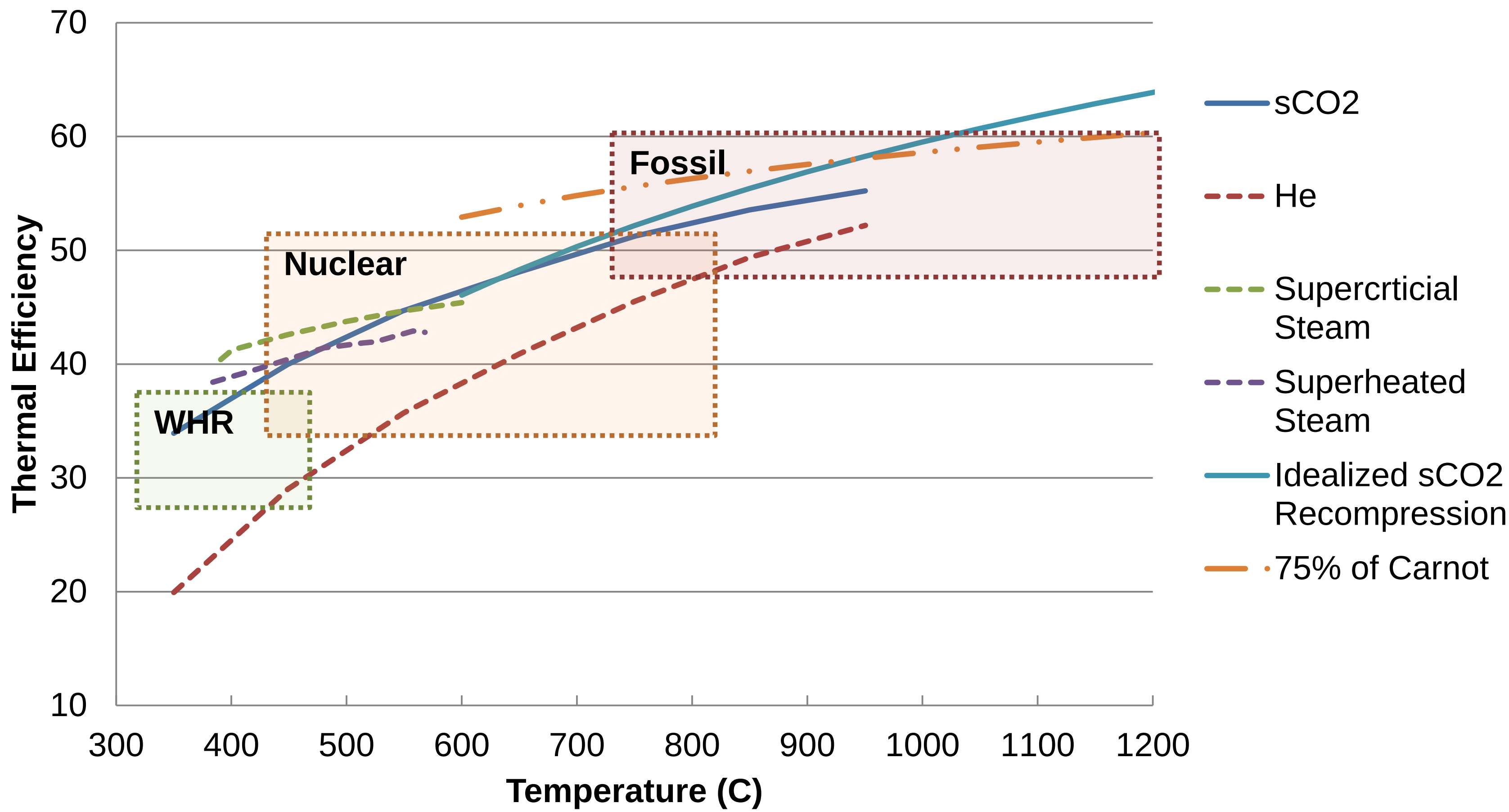
S-CO_2 Heat Exchanger and Power Cycle Projects

PROJECTS	2014	2nd	3rd	4th	2015	2nd	3rd	4th	2016	2nd	3rd	4th	2017	2nd	3rd
Sunshot - 5.5 MW Recuperator 1st Generation															
2nd Generation Recuperator - 100 kW															
Modular - 47 MW Recuperator 3rd Generation														Phase 2 Two years	
Sunshot - 2.5 MW Heater 1st Generation															
Oxy Combustion sCO2 Power Cycles															
Absorption/Desorption sCO2 Power Cycles															

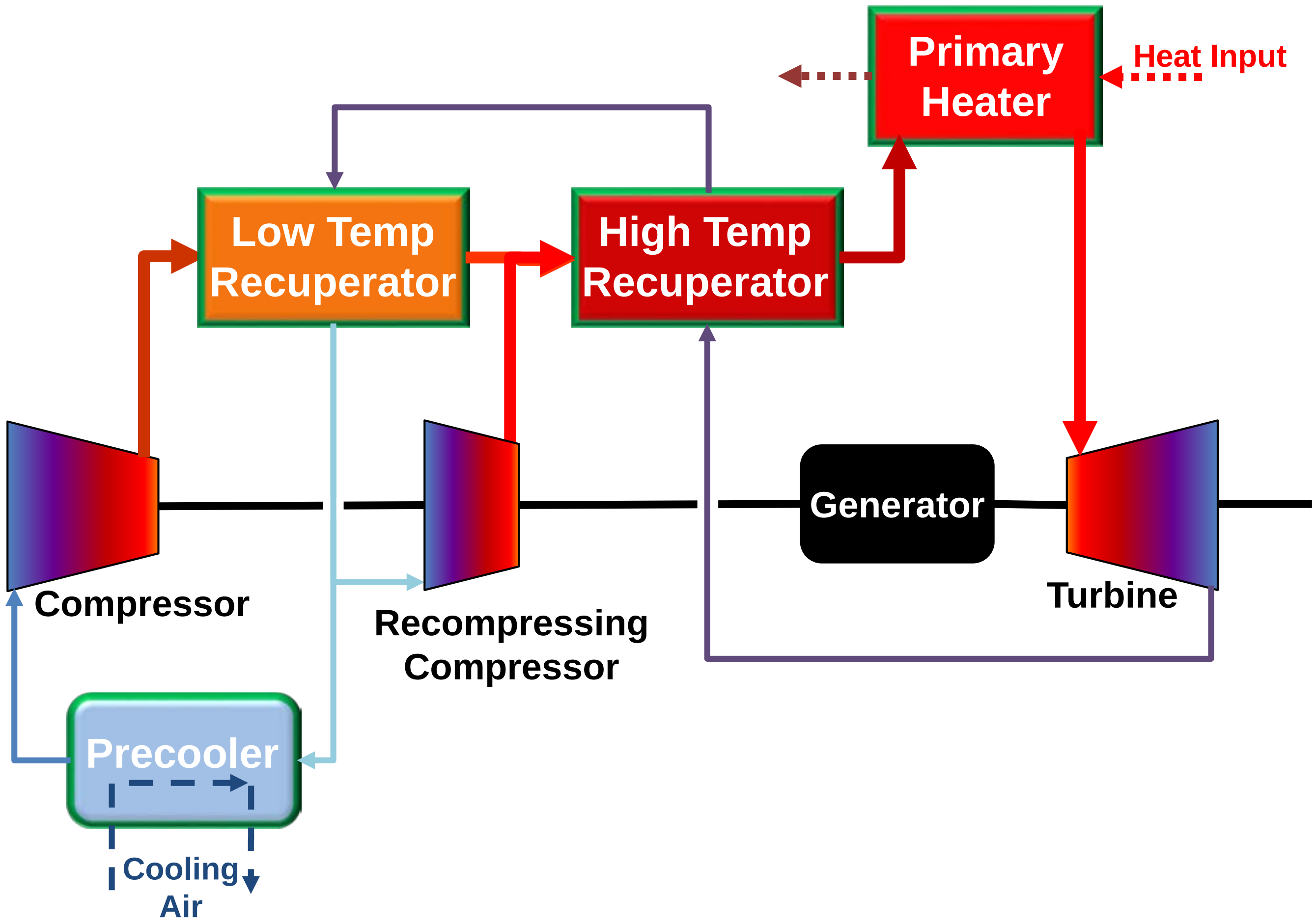


Why sCO_2?



sCO2, He, Supercritical Steam, and Superheated Steam are from Driscol MIT-GFR-045, 2008

Typical sCO_2 Recuperated Recompression Brayton Cycle



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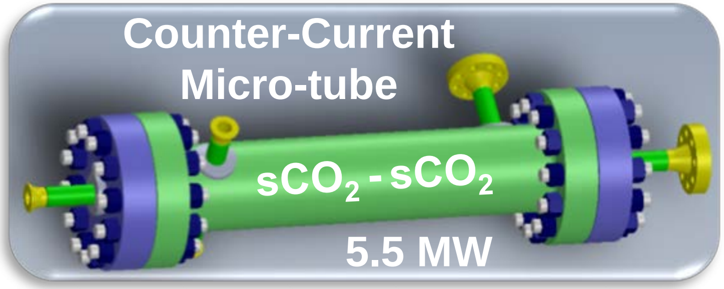
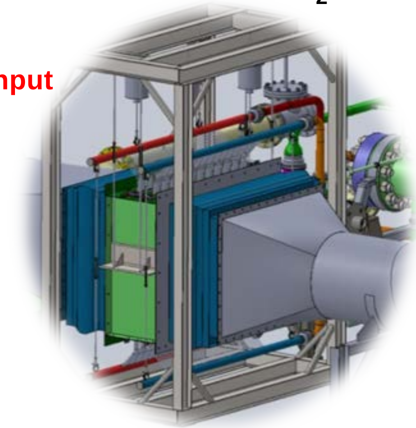
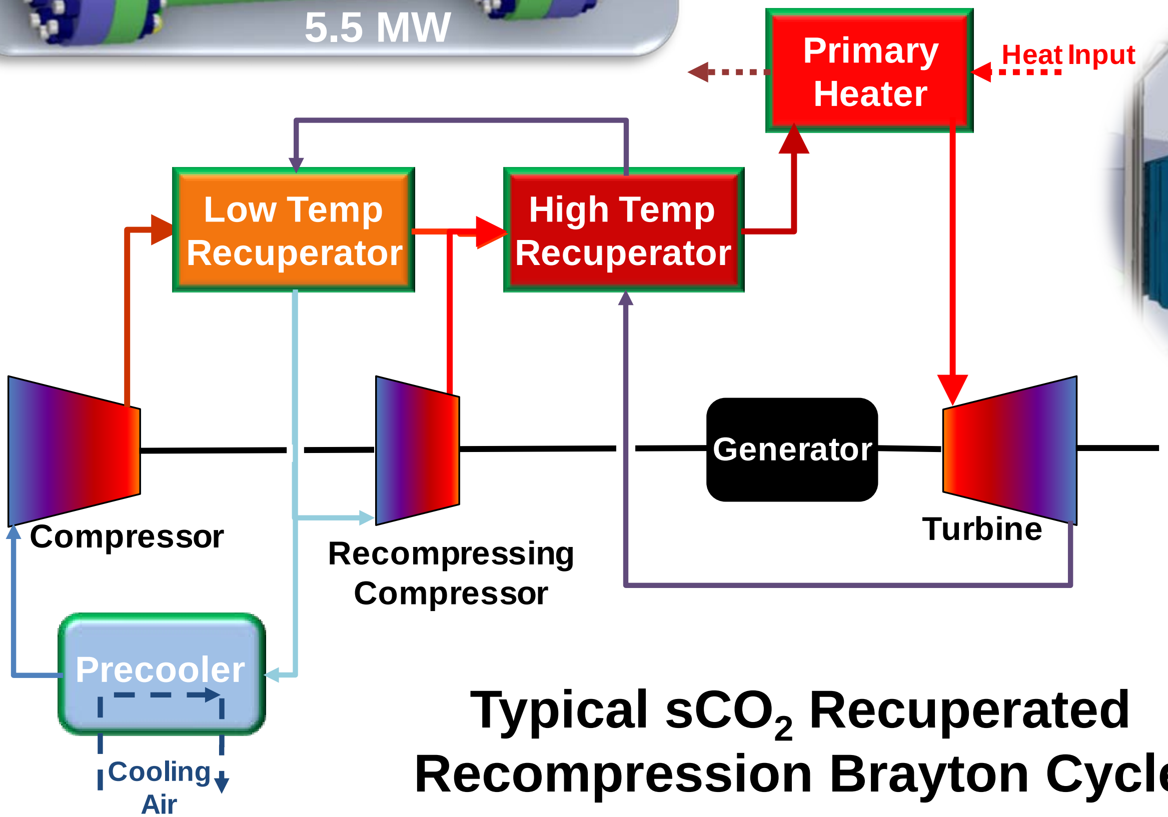
Thar Energy sCO_2
Recuperators, Heater HXs & Precooler HXs



2.5 MW Inconel 740H
Hot Air–sCO_2 HX





Typical sCO_2 Recuperated Recompression Brayton Cycle

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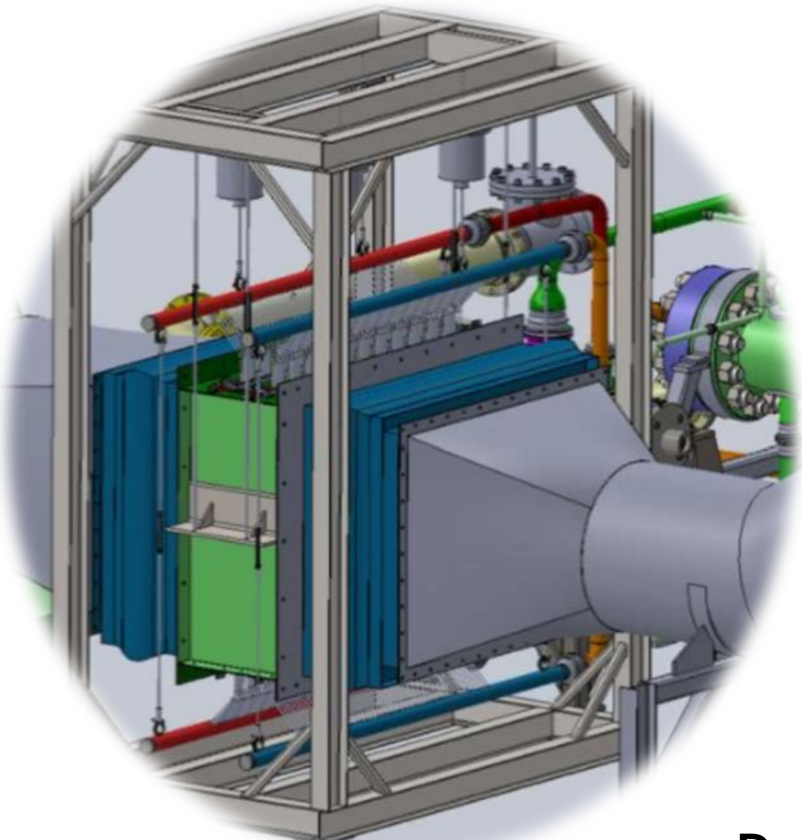
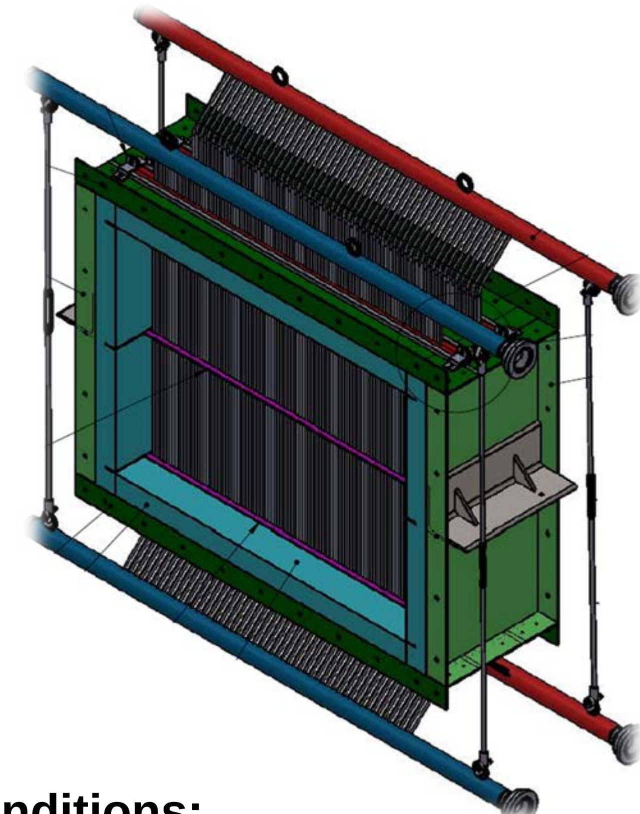
Sunshot Heater HX Design – 2.5 MW

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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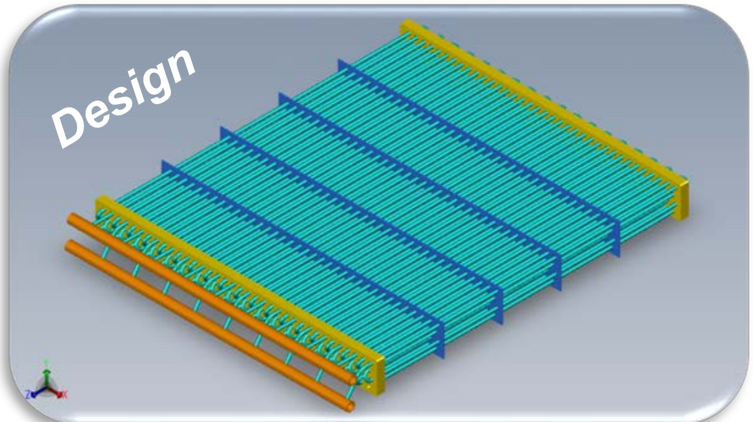
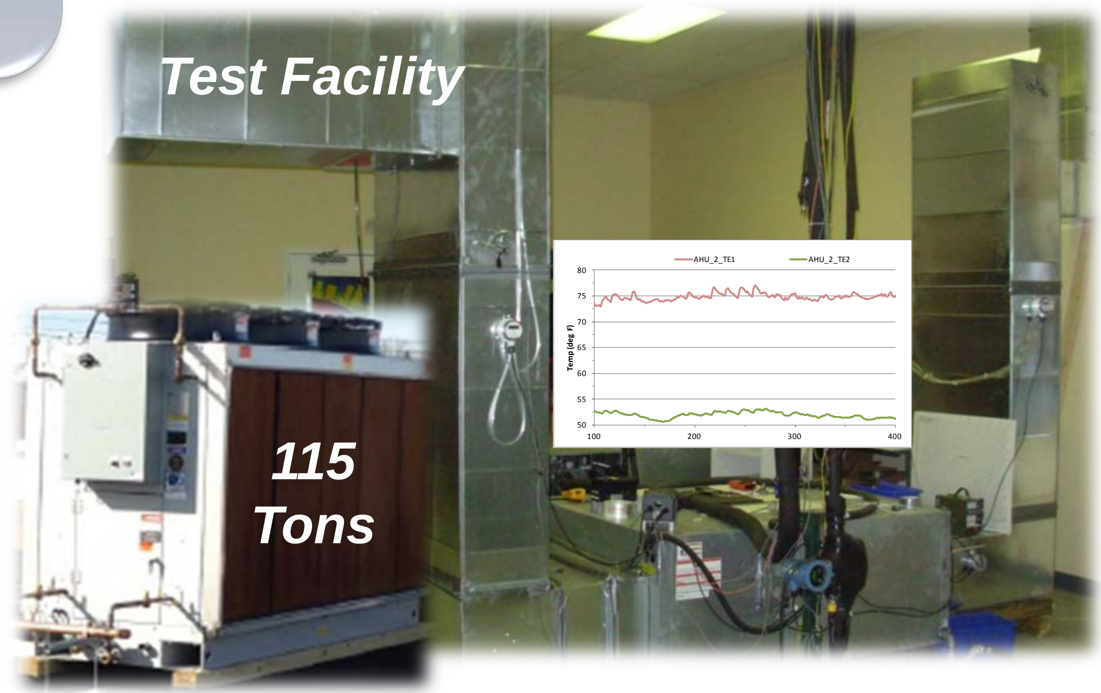
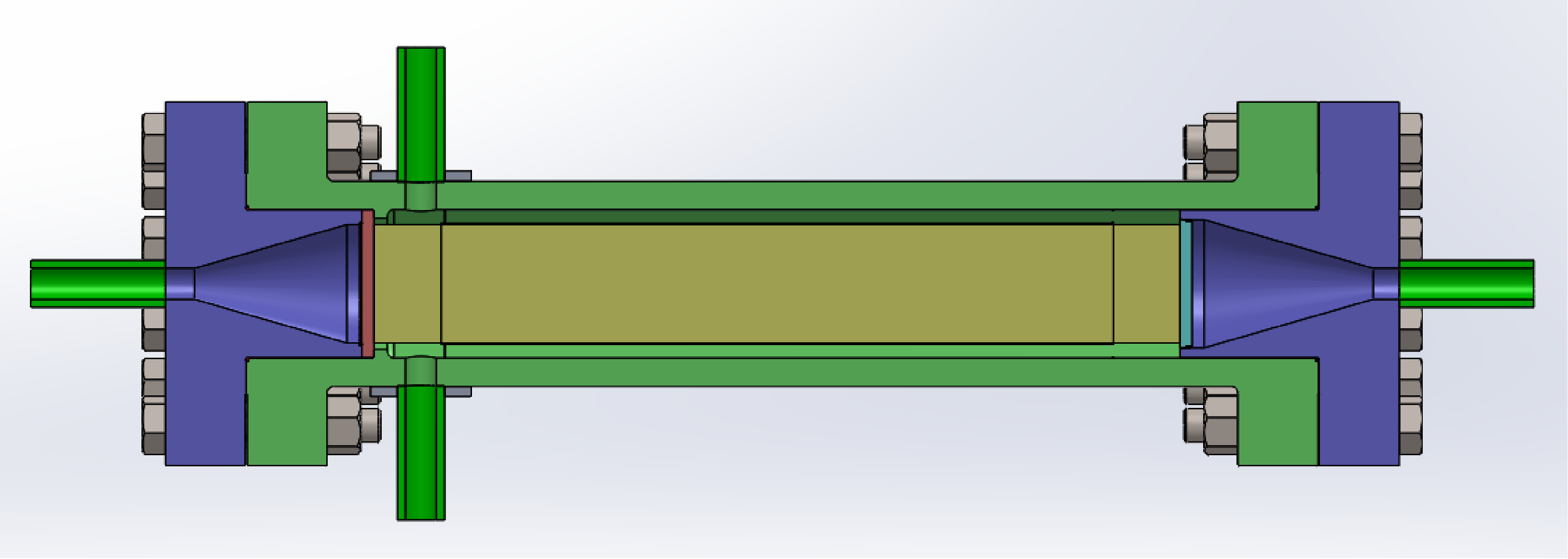
sCO_2 Gas Cooler HXs
35-500 kW

CO_2-Air Approach Temperature as Low as 2°C





1st Generation Recuperator Design



sCO_2 counter-current - microchannel heat exchanger

- Over 5 MW Capacity
- Operating Conditions: 567°C and 255 bar
- Design Conditions: 575°C @ 280 bar
- Floating Head Design
- Serviceability and Maintenance
- Replaceable Tube Bundle
- Easier to manufacture and assemble
- Small size of 9” Dia and 60” long

Designed per ASME Sec VIII, Div 1

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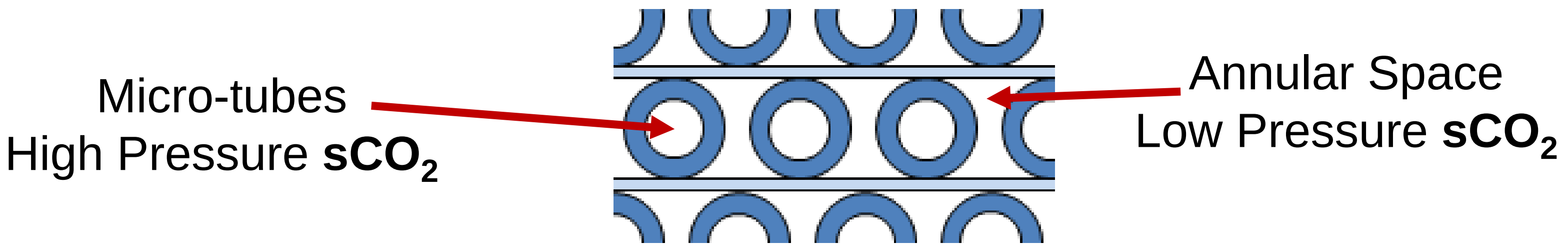
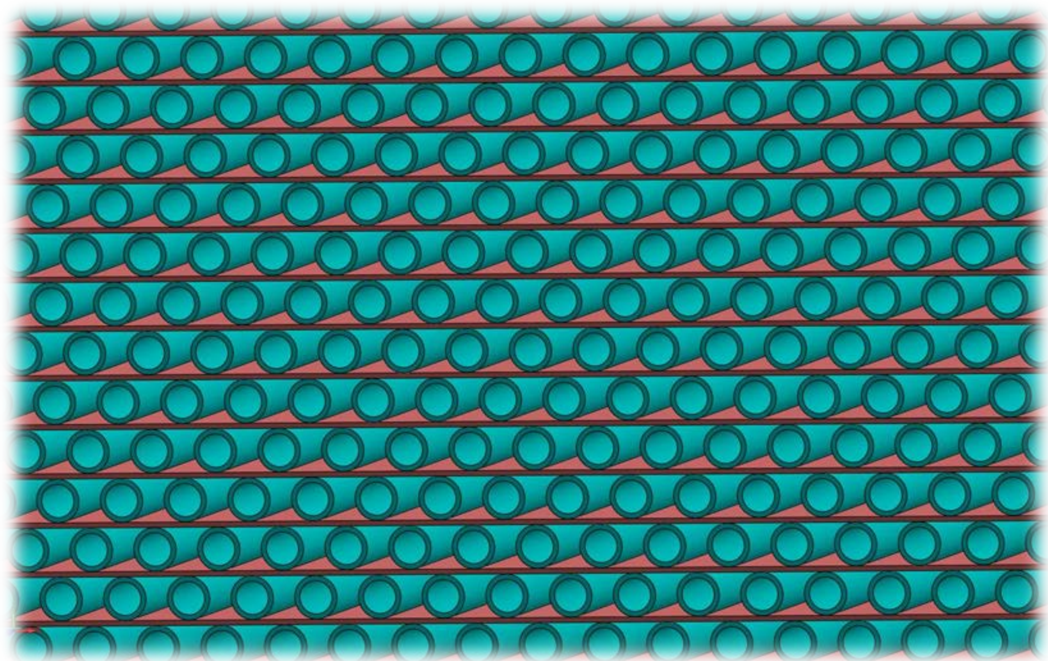
Sunshot Recuperator Tube Bundle



> 20,000 micro-tubes

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



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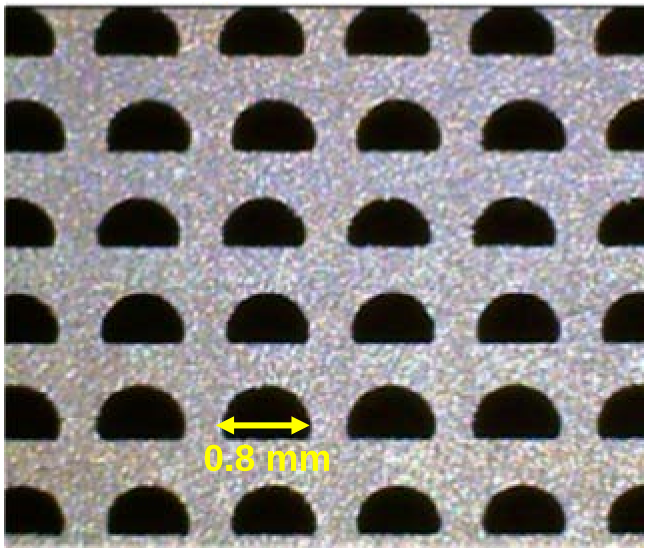
Recuperator Tube Bundle Cross Section

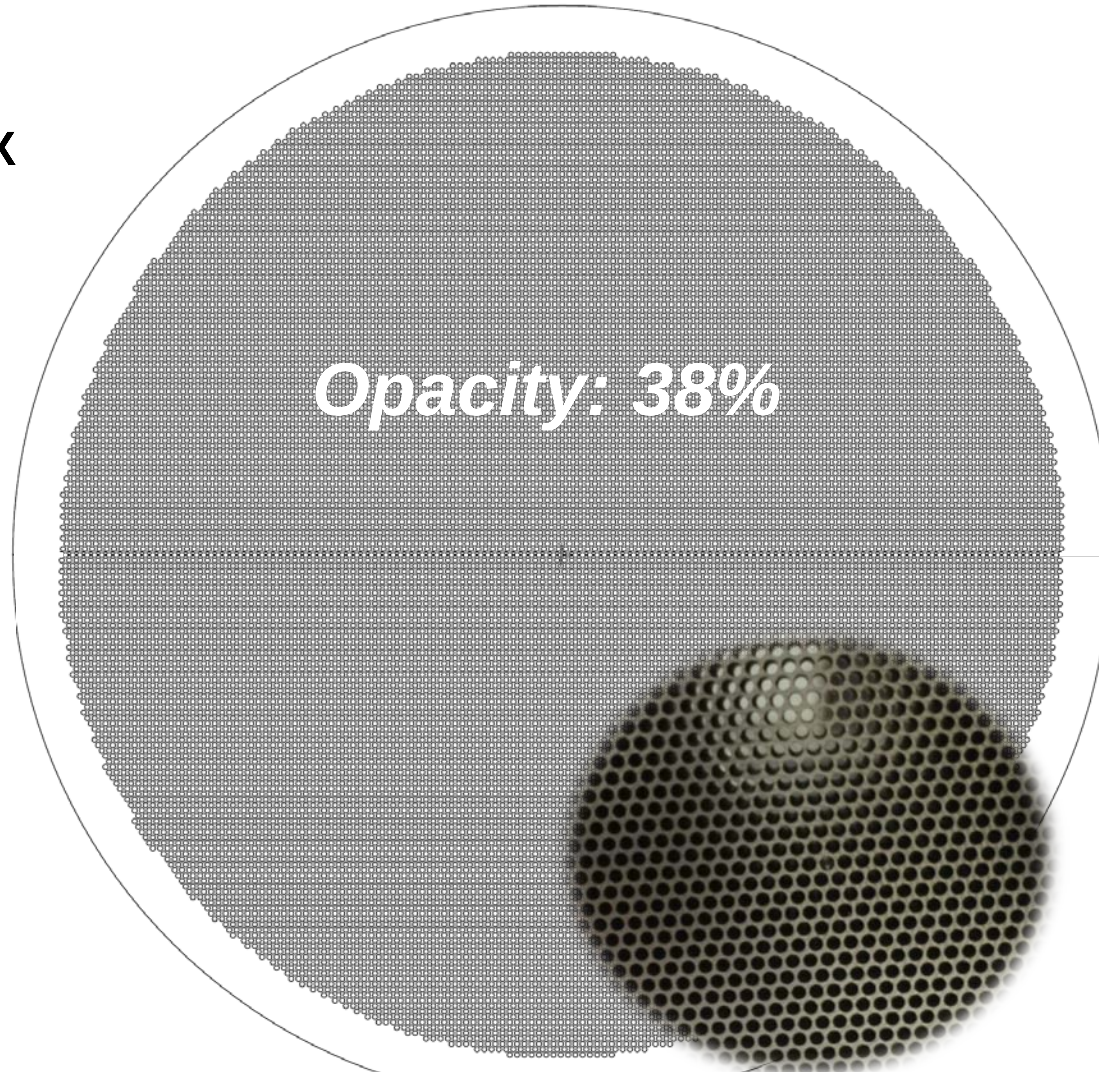
9” diameter, 5’ long, over 20,000 micro-tubes

Microchannel Printed Circuit HX



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

Opacity: 74%



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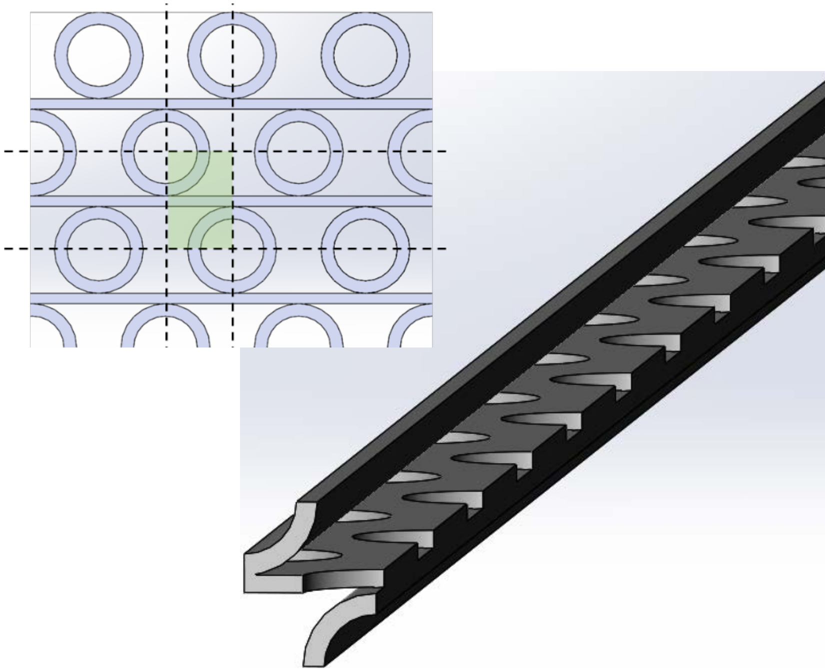
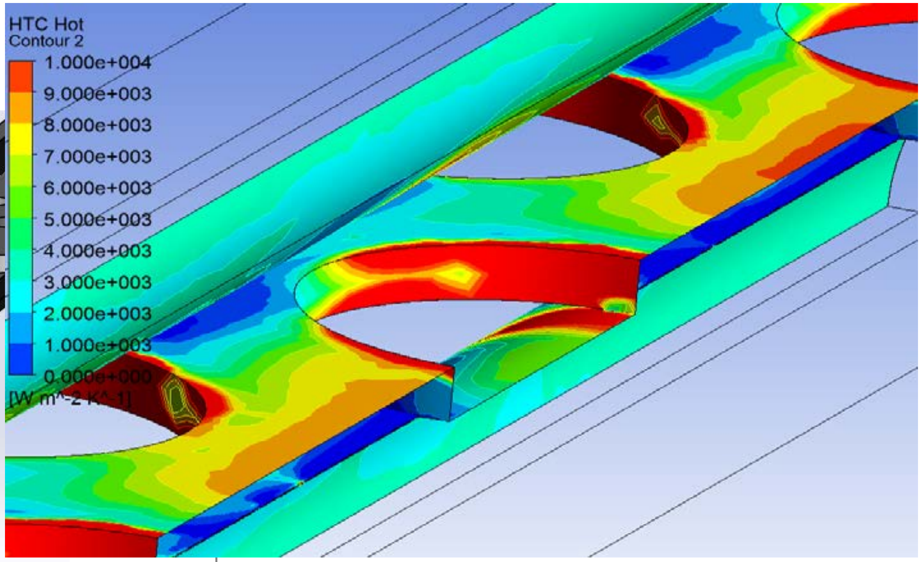
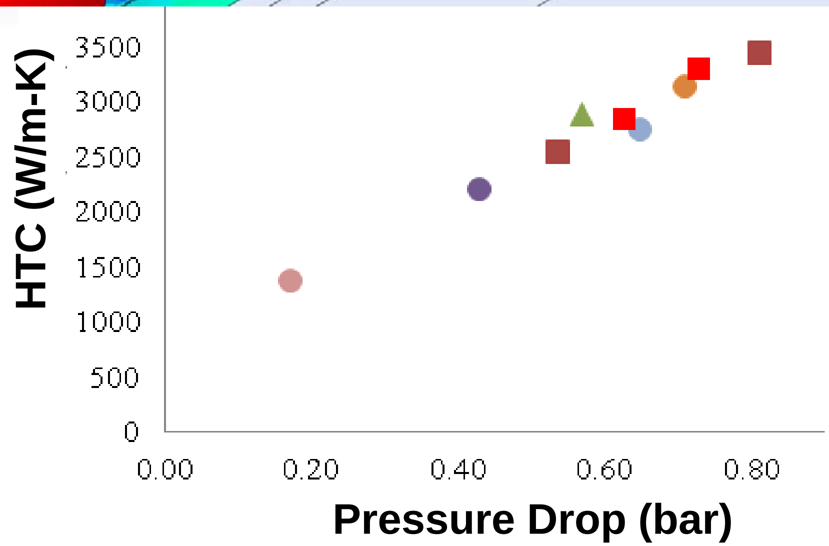
Perforated Separator Sheet Analysis

Improve the Pressure Drop to HTC ratio







~23% increase HTC &
~7% increase Pressure Drop

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Modular, Low-Cost, High-Temperature Recuperators for $sC0_2$ Power Cycles

- **Performance**
  - Temperatures ≥ 700°C
  - Differential pressures ~200 bar
  - Lifetime (corrosion, creep, etc.)
  - Ease of maintenance
- **Scalability**
  - 10 - 1,000 MWe Facilities
  - Transport
- **Cost < $100/kWt**
  - Materials Selection
  - Manufacturability

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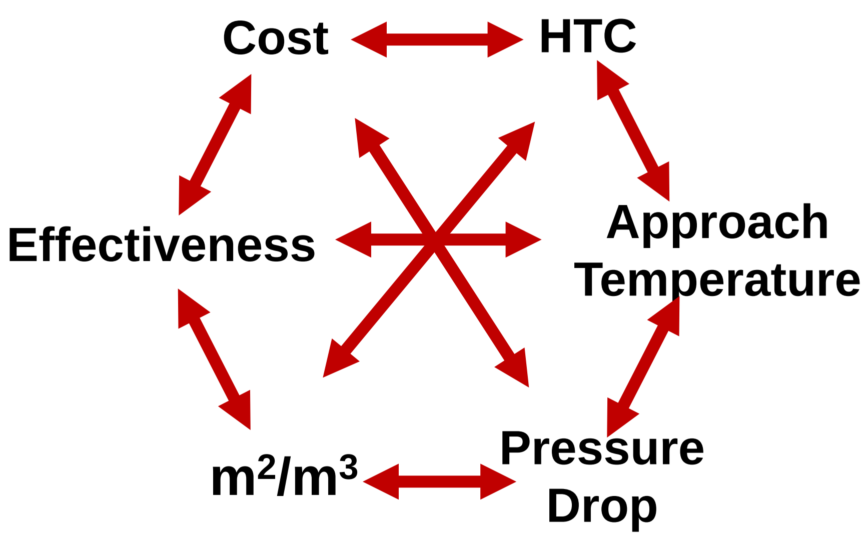
Focus of New Recuperator Designs

- Improve Performance/Cost Ratio
- Optimized materials' use for hot and cold sides
- Improved reliability
- Easier to assemble



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Modular, Low-Cost, High-Temperature Recuperators for $sC0_2$ Power Cycles

- **Engineering Assessment of Advanced Recuperator Concepts**
  - Critical enabling technologies or components
  - Manufacturability of the proposed concepts
  - Potential n^{th} of a kind production cost
  - Anticipated recuperator performance with respect to current state of the art

- **Prototype Fabrication, Testing and Evaluation**

- **Down Select and Fabrication of 47 MWt Recuperator**

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Modular, Low-Cost, High-Temperature Recuperators for $sC0_2$ Power Cycles

Timeline

	10/1/15-3/31/17						4/1/17-3/31/19							
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14
Phase 1														
Phase 2														

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Summary
Specializes in Low Cost Heat Exchangers Through Design and Manufacturability

- **Advanced Recuperators**
  - High Temperature Recuperators: up to 750 C
    - SS 316, Inconel 625, Inconel 740H
  - Low Temperature Recuperators
    - SS316, Aluminum
- **Advanced Heaters**
  - Up to 750 C
  - SS 316, Inconel 625, Inconel 740H
- **Coolers**
  - Aluminum microchannel heat exchangers
  - Approach temperatures of up to 2 C

Thank you for your kind attention!

Contact:

Lalit Chordia, PhD
Thar Energy, LLC
Pittsburgh, PA
412-963-6500
Lalit.Chordia@tharenergyllc.com
www.tharenergyllc.com

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ADDITIONAL BACKGROUND SLIDES

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“Typical” sCO_2 Cycle Conditions

Application	Organization	Motivation	Size [MWe]	Temperature [deg C]	Pressure [bar]
Nuclear	DOE-NE	Efficiency, Size	300 - 1000	400 - 800	350
Fossil Fuel	DOE-FE	Efficiency, Water Reduction	500 - 1000	550 - 1200	150 - 350
Concentrated Solar Power	DOE-EE	Efficiency, Size, Water Reduction	10, 100	500 - 1000	350
Shipboard Propulsion	DOE-NNSA	Size, Efficiency	10, 100	400 - 800	350
Shipboard House Power	ONR	Size, Efficiency	< 1, 1, 10	230 - 650	150 - 350
Waste Heat Recovery	DOE-EE ONR	Size, Efficiency, Simple Cycles	1, 10, 100	< 230; 230-650	15 - 350
Geothermal	DOE-EERE	Efficiency, Working fluid	1, 10, 50	100 - 300	150

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Fossil Based sCO_2 Power Cycles

- Competition
  - Indirect: Supercritical Steam with CCS
  - Direct: Natural Gas Combined Cycle
- Advantages
  - High power efficiencies at “Moderate” temperatures
  - Oxy-combustion facilitates integrated carbon capture
  - Compact turbomachinery lead to compact power blocks
  - Partially offset by recuperation to achieve high cycle efficiencies
- Challenges
  - 250 C thermal input temperature widow (recompression cycle) is not ideal for combustion based systems
    - 400 C Combustor inlet for 650 C Turbine Inlet
    - 950 C Combustor inlet for 1200 C Turbine inlet
  - Flue gas cleanup for direct fired systems
  - Non-trivial efficiency losses for indirect cycles

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Nominal 10 MWe RCBC test facility