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Enabling the Extraordinary
To Fly To Power To Live

Challenges and Development of sCO2 heat exchangers

Heatric

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Business Development Engineer

DOE sCO2 Workshop October 2019

Organisation structure

New customer-focused organisation aligned to end markets

Airframe Systems

- Braking Systems
- Fire & Safety
- Power & Motion
- Avionics & Airframe Sensing
- Polymer Seals
- Fuel Systems & Composites

Engine Systems

- Flow Control
- Thermal Systems
- Engine Composites
- Engine Sensors

Energy & Equipment

- Defense Systems
- Training Systems
- Heatric
- Energy Sensors & Controls

Services & Support

- Americas
- UK & Europe
- Asia Pacific

Effective January 1, 2019, Meggitt has adopted a new organisation structure, designed to accelerate growth by increasing alignment with our customers whilst simplifying our business.

Heatric Timeline

1985 - Present

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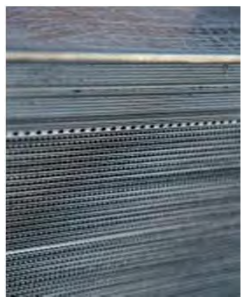
1980



PCHE developed at University of Sydney

1985

Heatric founded in Australia, later relocated to UK in 1990

1989

Heatric's first application in offshore gas processing

1998

Heatric open sales office in Houston, TX, USA

2010

Heatric expand, open sales office in Brazil

2013

Heatric opens new Holton Heath Factory

2015

Heatric opens sales office in Singapore in 2015, and South Korea in 2017

2017

Heatric gain nuclear certification

2019

Meggitt and Heatric rebranded

Main sCO2 cycles

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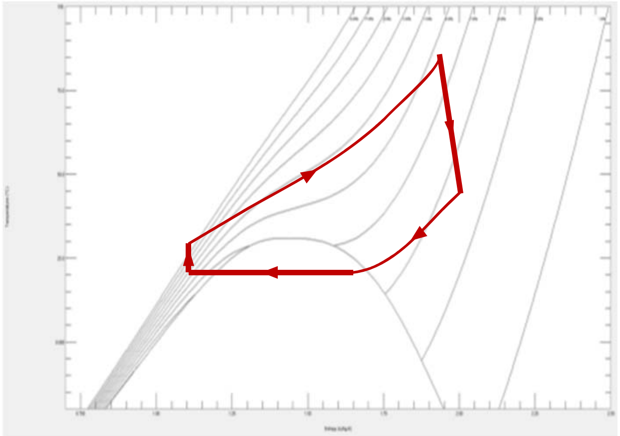
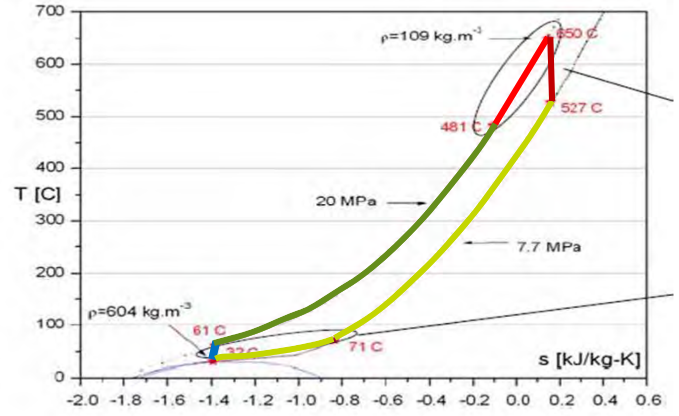
Rankine sCO2 Cycle



Bottoming cycles

Mostly used as waste heat recovery applications for gas turbines, industrial heat and high temperature geothermal in the 10s MWe range

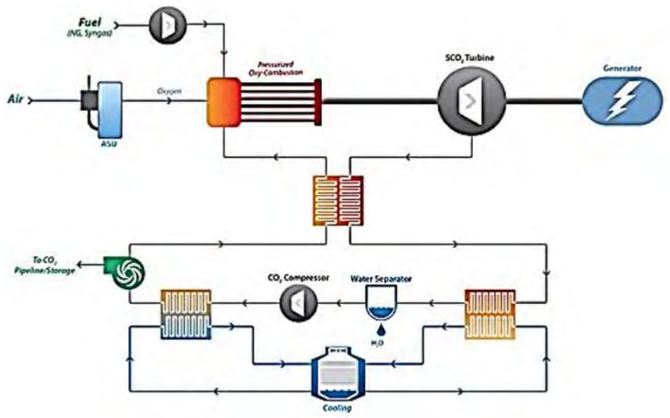
Brayton sCO2 Cycle



Baseload cycles

Developed to displace steam for Fossil, Nuclear and CSP applications for 100s Mwe range

Oxy-fuel sCO2 Allam Cycle



Baseload with Carbon capture

Developed to provide electricity at high efficiency with 100% carbon capture and displace fossil plants with CCS in the 100s MWe range

sCO2 Cycles

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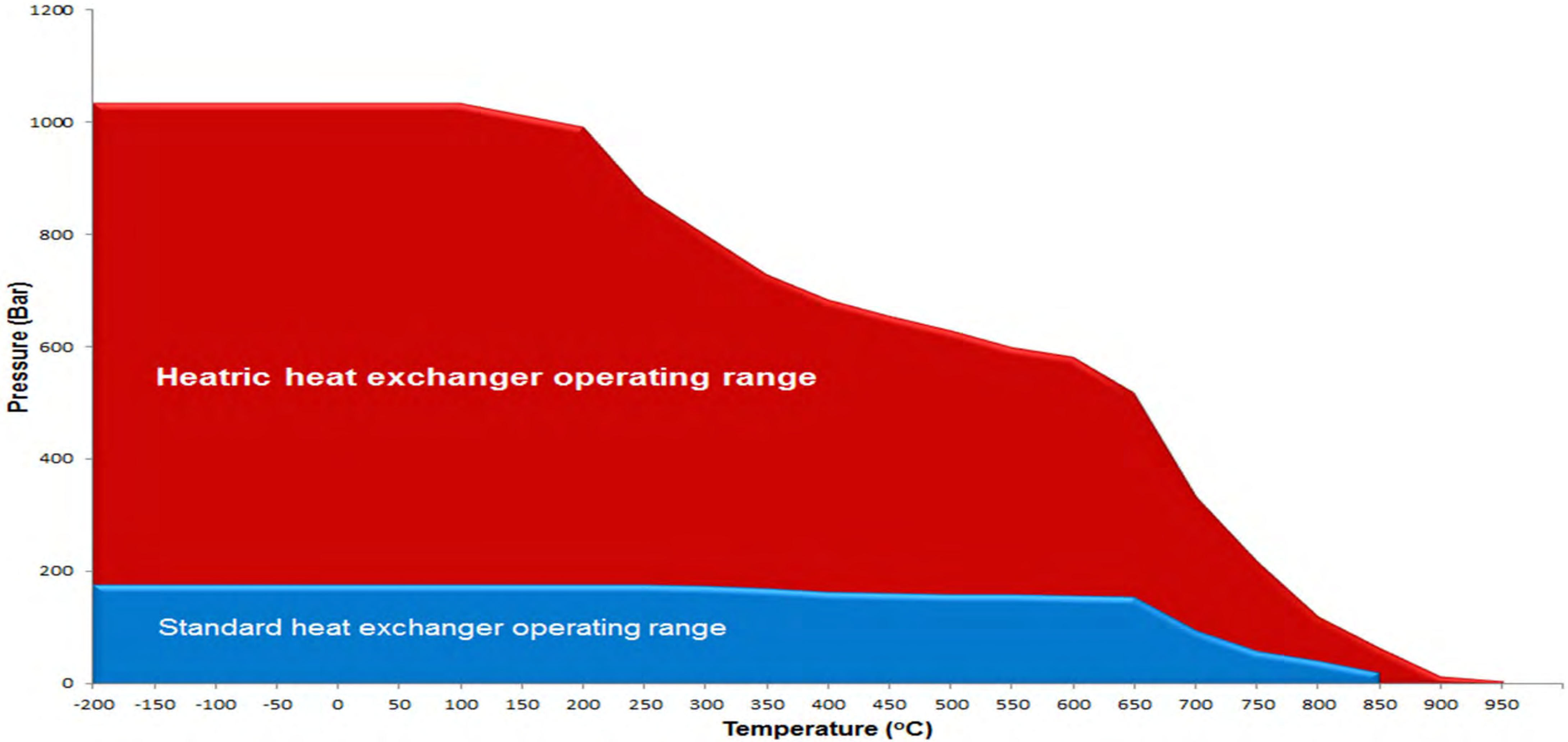
Application	Cycle type	Motivation	Size [MWe]	Temperature (°C)	Pressure [MPa]
Nuclear	Indirect sCO_2	Efficiency, Size, Water Reduction	10 - 300	350 - 700	20 - 35
Fossil Fuel (PC, CFB, …)	Indirect sCO_2	Efficiency, Water Reduction	300 - 600	550 - 900	15 - 35
Concentrating Solar Power	Indirect sCO_2	Efficiency, Size, Water Reduction	10 - 100	500 - 1000	35
Shipboard Propulsion	Indirect sCO_2	Efficiency, Size	<10 - 10	200 - 300	15 - 25
Shipboard House Power	Indirect sCO_2	Efficiency, Size	<1 - 10	230 - 650	15 - 35
Waste Heat Recovery	Indirect sCO_2	Efficiency, Size, Simple Cycles	1 - 10	< 230 - 650	15 - 35
Geothermal	Indirect sCO_2	Efficiency	1 - 50	100 - 300	15
Fossil Fuel (Syngas, nat gas)	Direct sCO_2	Efficiency, Water Reduction, CO_2 Capture	300 - 600	1100 - 1500	35

Extract from DoE Quadrennial Technology Review 2015 - Chapter 4: Advancing Clean Electric Power Technologies

PCHE pressure and temperature design range



What is a Heatric PCHE?

Printed Circuit Heat Exchangers

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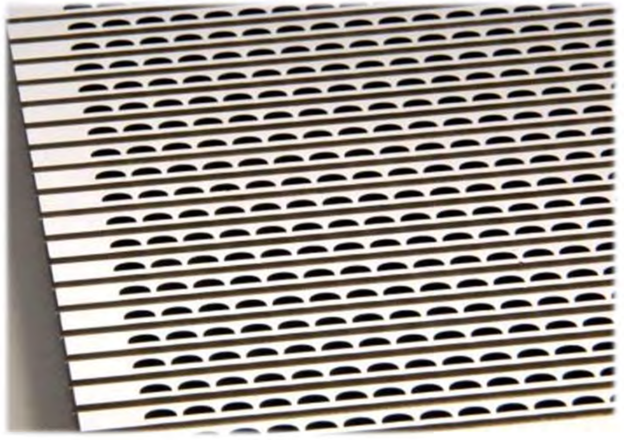
Superior Performance

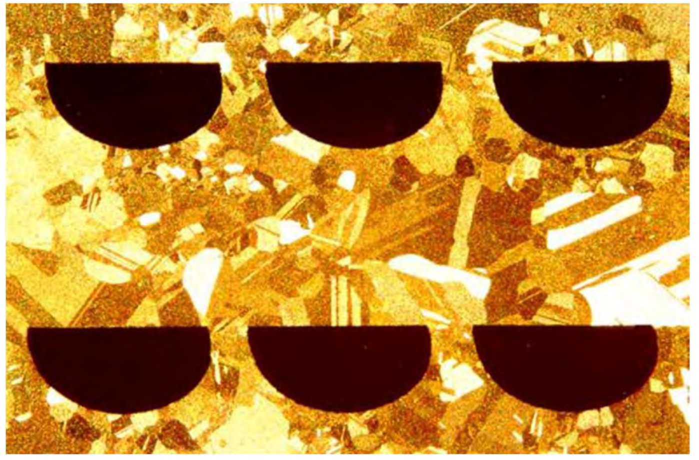


OPEX saving across wide range of processes

Heatric PCHEs are bespoke diffusion bonded compact heat exchangers providing:

- close temperature approaches (>2°C)
- very high thermal performance (i.e. 13.6MWth/m^3 sCO_2 recuperator)
- high pressure capability (>1,000 Bar)
- widest range of temperatures (-196°C to 983°C)

Safe



Reduced operational risks

Using diffusion bonding with a fully welded construction, PCHEs:

- can operate at full differential pressure between streams
- are immune to flow induced vibrations and pressure fluctuations
- do not suffer from catastrophic failure mode
- have 30 years track record of safe operation and >3,000 exchangers supplied

Compact and Modular

Overall project CAPEX saving

Heatric PCHEs are up to 85% smaller than Shell and Tube exchangers, offering:

- modularisation for ease of transport, on-site installation
- reduced foundation structure
- reduced pipework and safety valves
- retrofit capability in lieu of S&T

Heatric sCO2 Key Delivered Project Timeline

Since 1994

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1994

First PCHE using sCO2 – Offshore re-injection

2003

Heatric supply to their first PCHE Recuperator for Tokyo Institute of Technology sCO2 loop

2009

Heatric's supply three PCHEs to Sandia National Laboratories sCO2 Brayton test loop

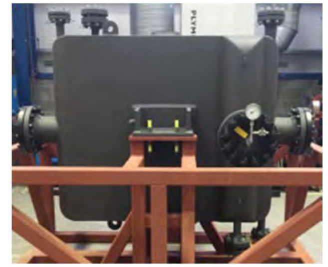
2011

Heatric supply to Echogen EPS 100, the world's first commercial sCO2 WHR unit

2016

Heatric supply to NETPower Pilot Plant in Texas

2017



Heatric supply to China Western Power Company Biomass test loop

2019

Several on-going WHR and Baseload projects

Heatric sCO2 Exchangers – 18 Major Projects to date*

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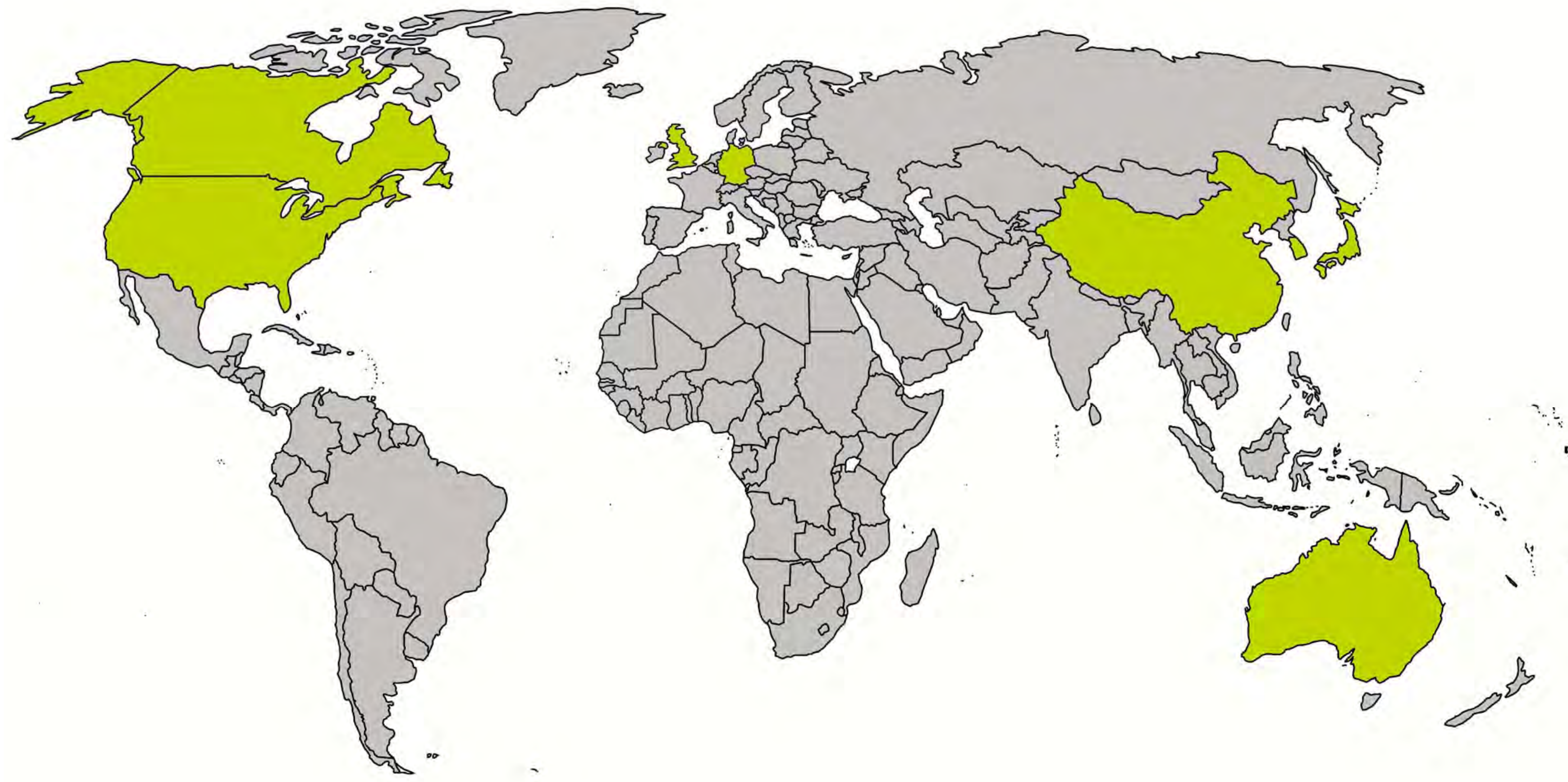
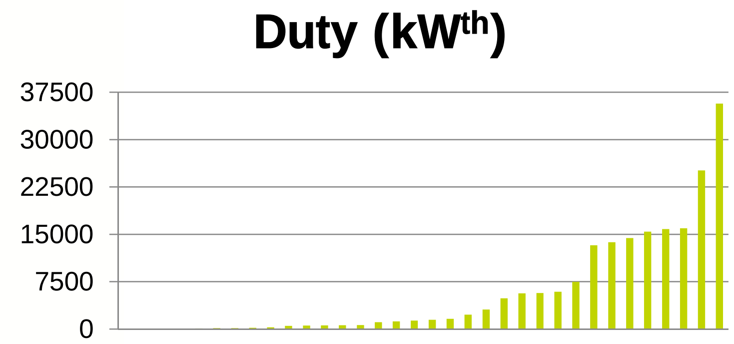
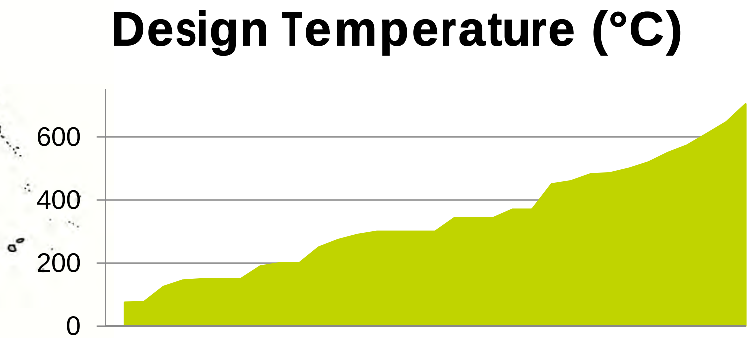
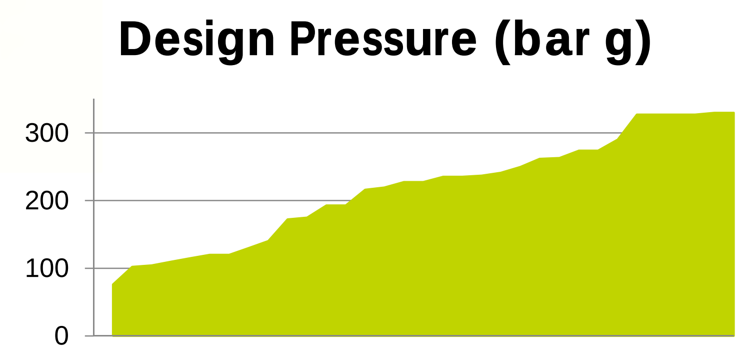


	USA	Australia	U.K.	Germany	Canada	China	Japan	Korea
N° Project	10	1	2	1	1	1	1	1
N° Units	21	3	2	2	2	2	1	1

* 40 sCO2 exchangers delivered, 270 sCO2 projects quoted, >1,000 exchangers bespoke designs







Heatric Component cost – 316, 347, 617 Pipe (ASME B31.3)

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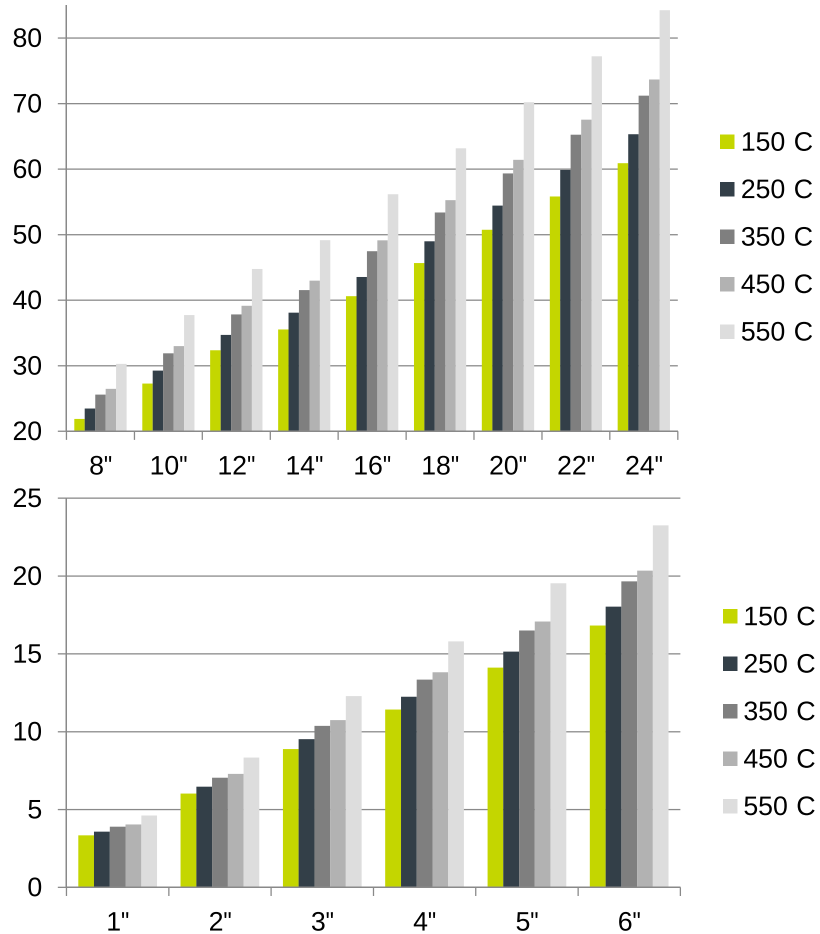
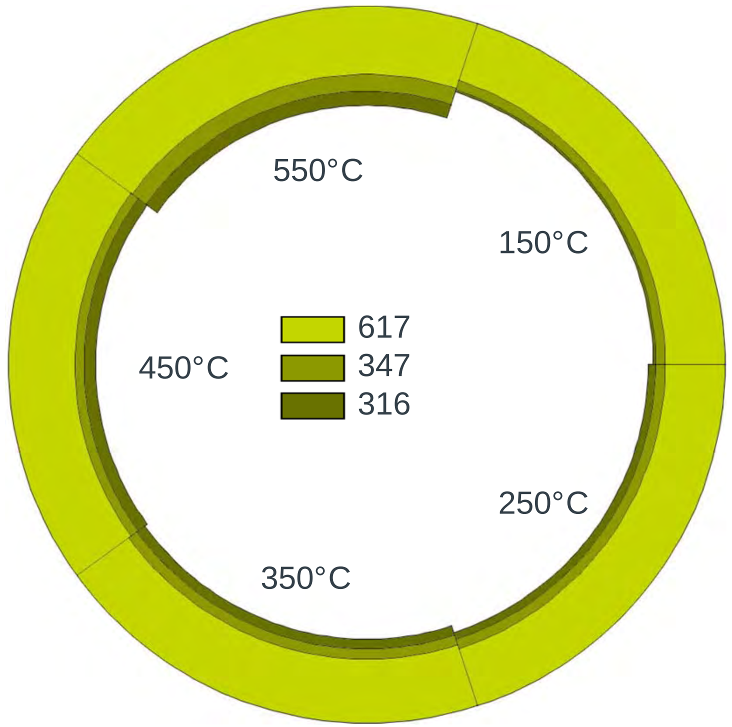
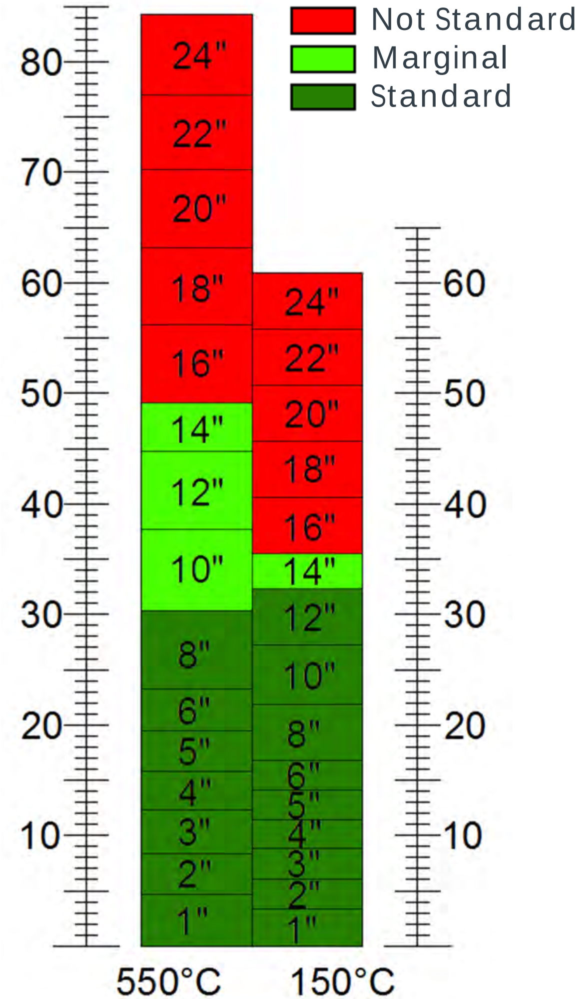


316 Pipe thicknesses vs. design temperature (250 Bar design pressure)



	150°C	250°C	350°C	450°C	550°C
316 vs 347	3%	9%	12%	13%	14%
316 vs 617	17%	22%	24%	23%	31%

316, 347, 617 Pipe thickness reduction vs. temperature (250 Bar pressure)



316 Pipe thickness vs. Std Pipe schedule (250 Bar pressure)

Lesson learned

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sCO2 heat exchangers are expensive?

Yes they can be depending on the process design:

Increasing design temperature:

- May shift equipment built from conventional material to high grade alloys (10x – 20x more expensive)

Increasing design Pressure:

- Will require thicker walls with much more expensive non standard product forms for some components (i.e. hubs, special forgings, pipes)

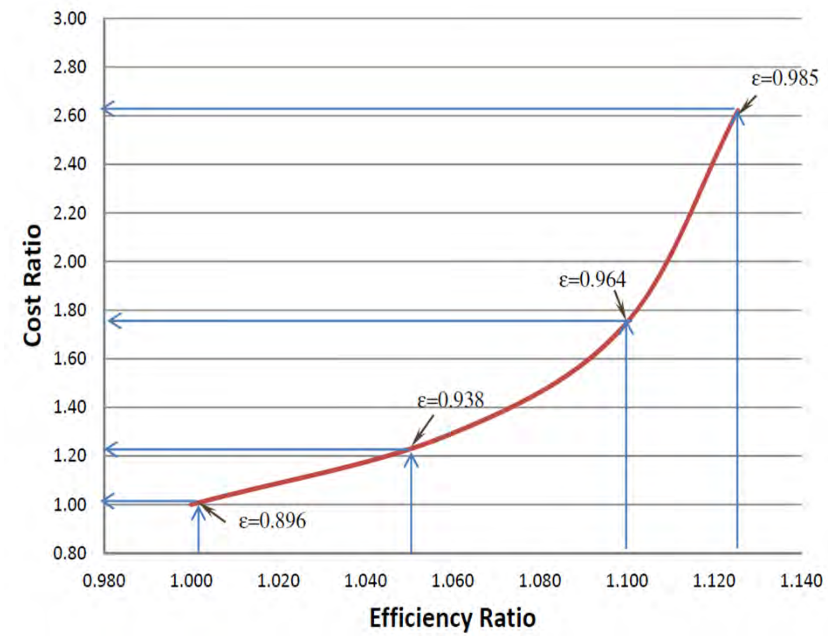
Temperature approaches:

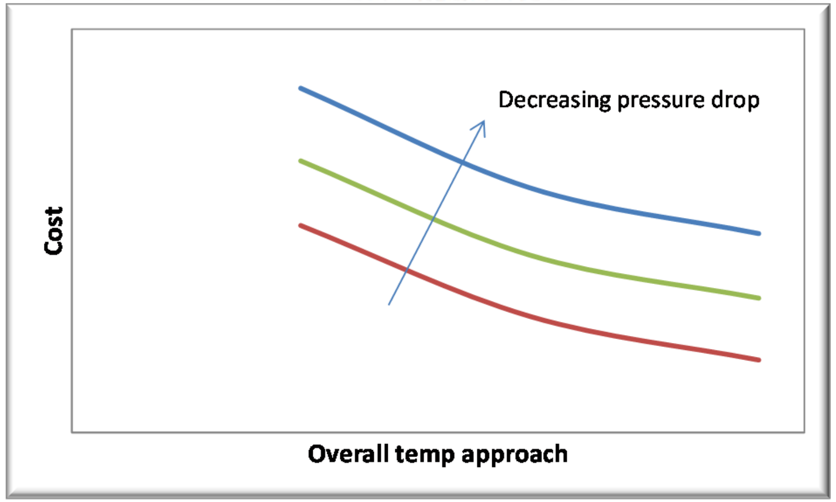
- Will lead to diminish efficiency returns versus exchanger potentially doubling in size for minimum gains(Q=U.A.LMTD)

Allowable pressure drop:

- Will lead to very high free flow area requirements increasing the size of the exchanger potentially beyond compressor / pump cost savings

sCO2 process design must be balanced between equipment cost and efficiency gain





Path to commercialisation

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Supply Chain

Cost reduction
Product availability

Even in stainless steel, material price and product form availability can be a challenge; Supply chain must be engaged with to providing competitive materials in suitable product forms.

Standardisation

Process | Products
Performance

Standardisation of the various sCO_2 processes will lead to standard products, potential for off-the shelf with mass production and guaranteed performance based on previous supplies results operational records.

Making sCO_2 Viable?

Modularisation

Flexibility | Footprint
Plant integration | Deployment

Modularisation brings benefits in flexible designs with minimum changes, defined footprints facilitating plant integration and facilitation deployment even in remote area (i.e. containerized).

Collaboration

Faster R&D | No duplication
Better use of funds

Improve international coordination / communication to ensure most R&D activities going forward are not replicating existing research in other territories / regions.

Technology development

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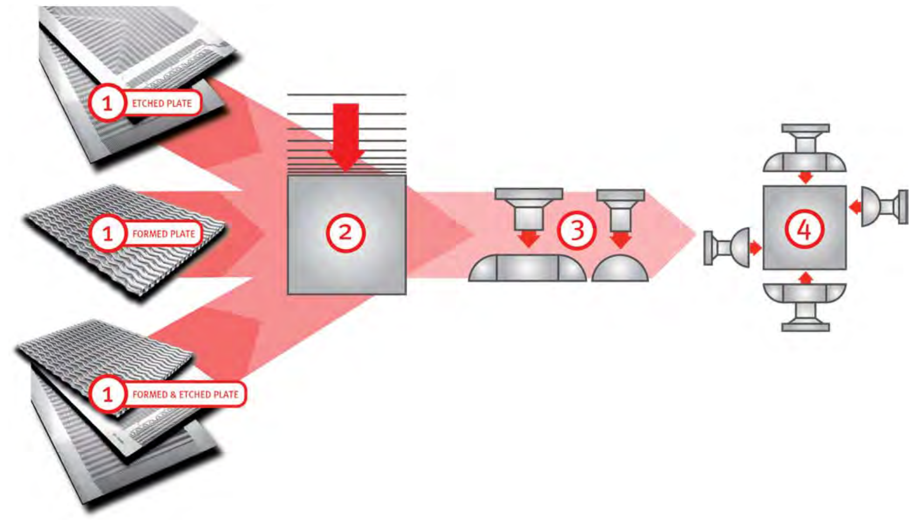
PCHE

PCHEs typical channels are 1 mm deep (2 mm semi circular)

They are well suited for sCO_2 but not for exhaust side due to pressure drop constrains

PCHEs are already used as Recuperators in sCO_2 systems

Heatric has developed deep etch technology currently able to achieve 2.5 mm deep channel (5 mm semi circular)



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H^2Xs aim to combine 2 or more different product forms in a single product

To date H2X has been considering combining Fins to PCHE channels

Work is in progress to validate H^2X as part of the Cranfield test loop

Further work is on-going to expand channel size on the exhaust side to $dH > 5$ mm

Sandia National Laboratories – sCO2 Brayton Cycle

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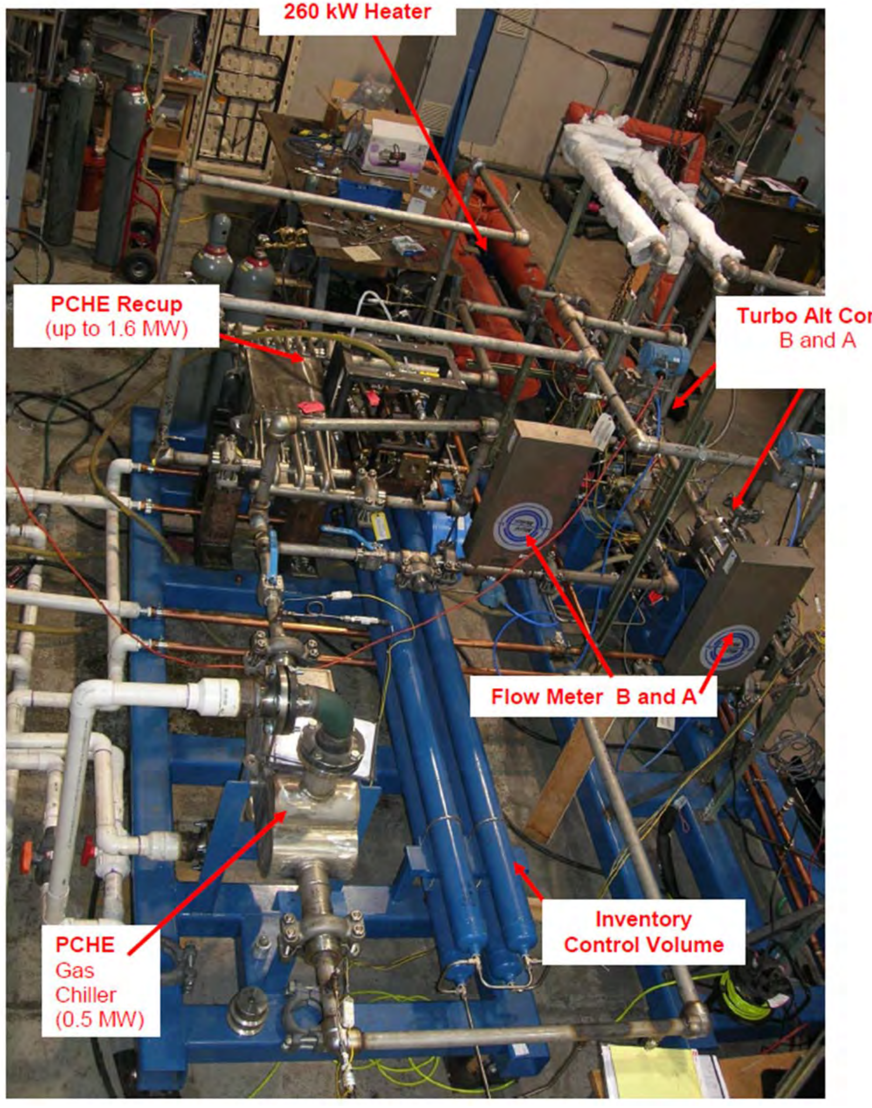
- HT Recuperator
  - 2.27 MW
  - 482°C (900°F)
  - 17.24 MPa (2500 psig)

- LT Recuperator
  - 1.6 MW
  - 454°C (849°F)
  - 17.24 MPa (2500 psig)

- Gas Chiller
  - 0.53 MW
  - 149°C (300°F)
  - 19.31 MPa (2800 psig)

3 sCO2 exchangers delivered

>2.2 tons combined



Echogen EPS100 – sCO_2 Rankine Cycle

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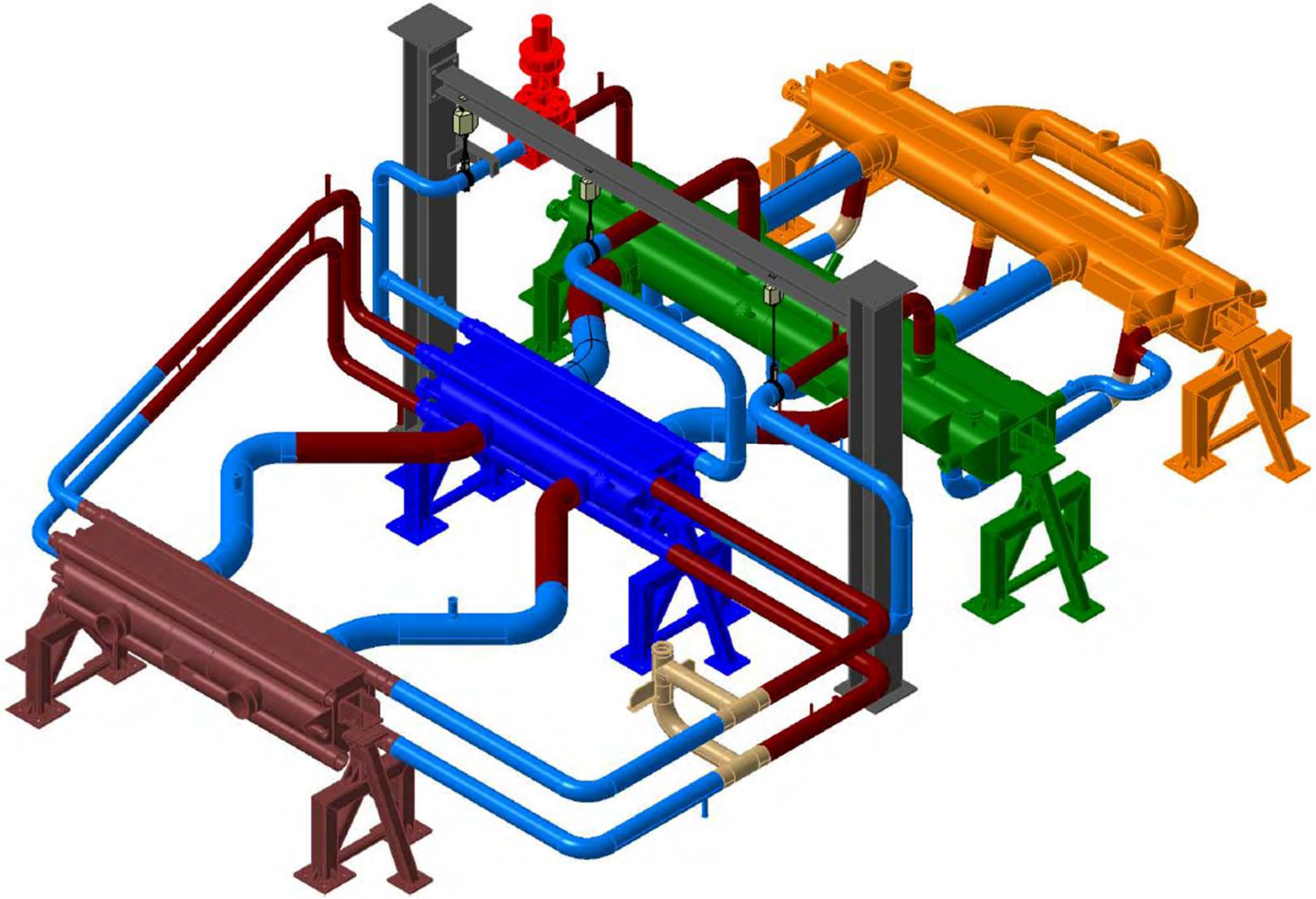
3 sCO_2 exchangers delivered

>30 tons combined

Net Power 25MWe – sCO2 Oxy Fuel Allam Cycle



4 sCO2 exchangers delivered (including one 617 unit)
60 tons combined

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