Tutorial:

Heat Exchangers for Supercritical CO2 Power Cycle Applications

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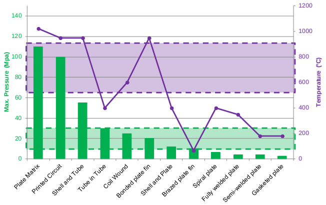
The following slides present an overview of heat exchangers in supercritical CO_2 applications



Heat Exchangers in sCO2 power cycle applications

System Optimisation for Heat Exchangers

HEXs suited for s-CO2 applications

Heat Exchanger Mechanical Design for S-CO2

Hydraulic Design with Supercritical Fluids

Questions

Heat Exchangers in sCO2 power cycles applications

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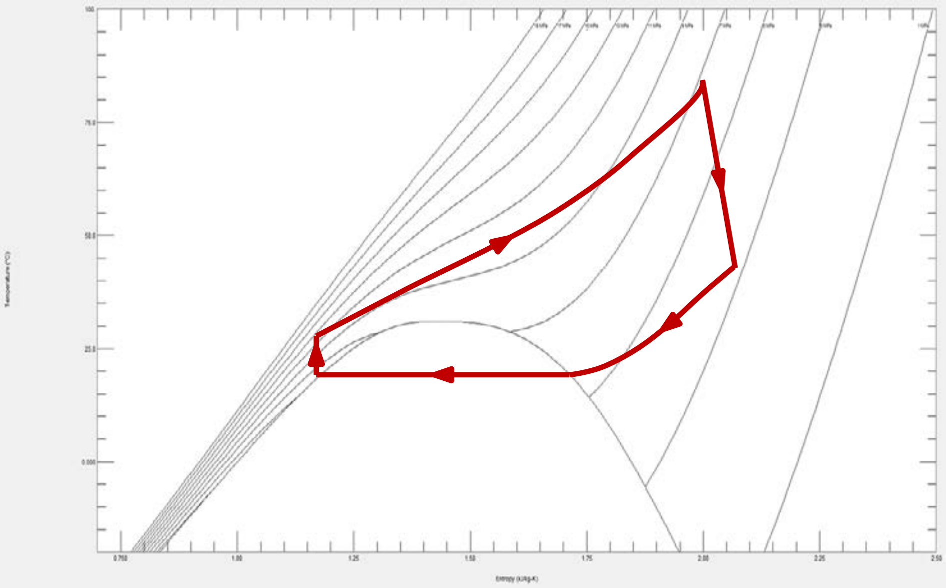
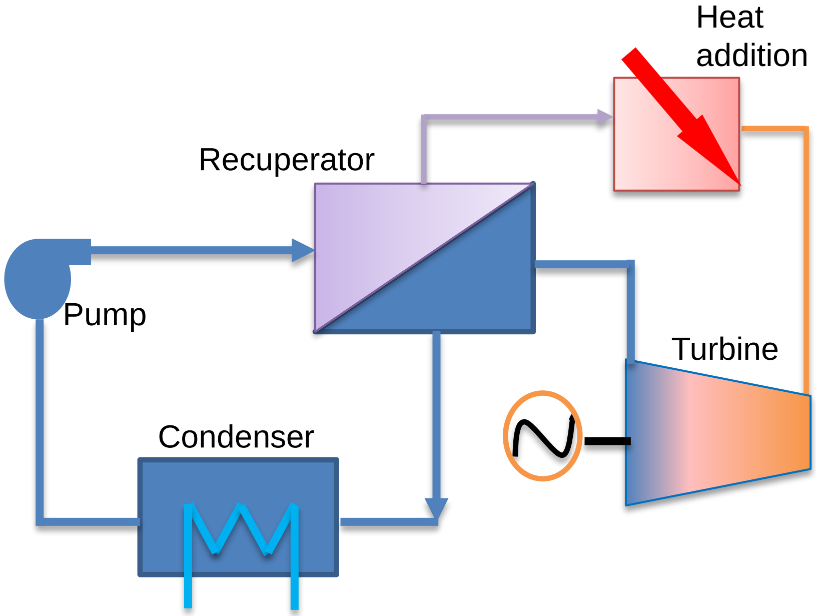
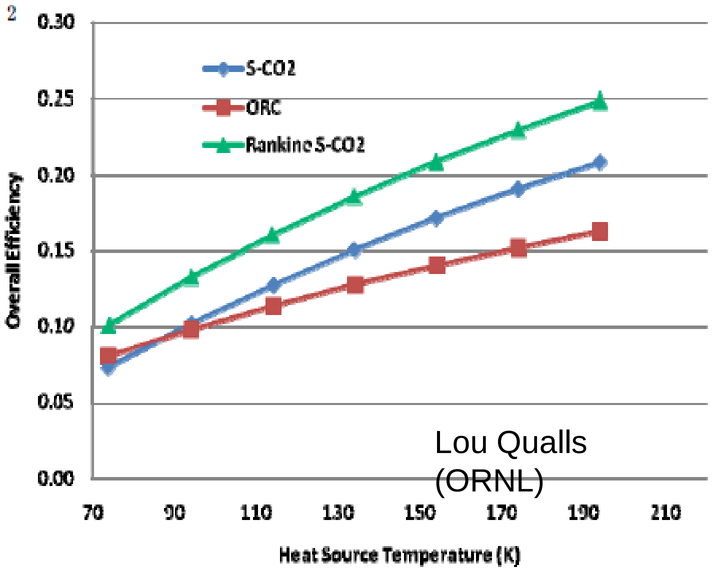
S-CO$_2$ Rankine Cycles



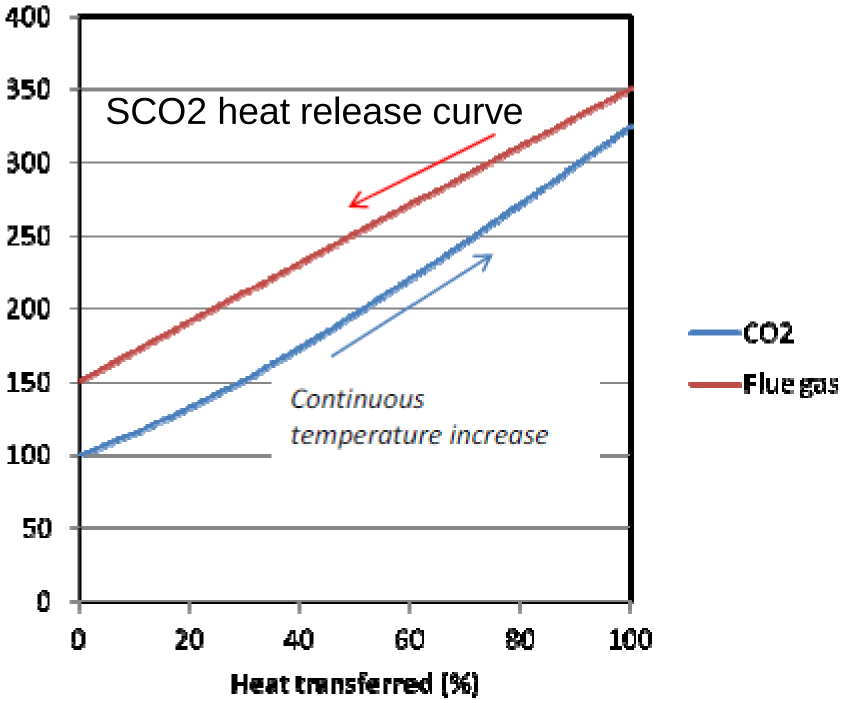


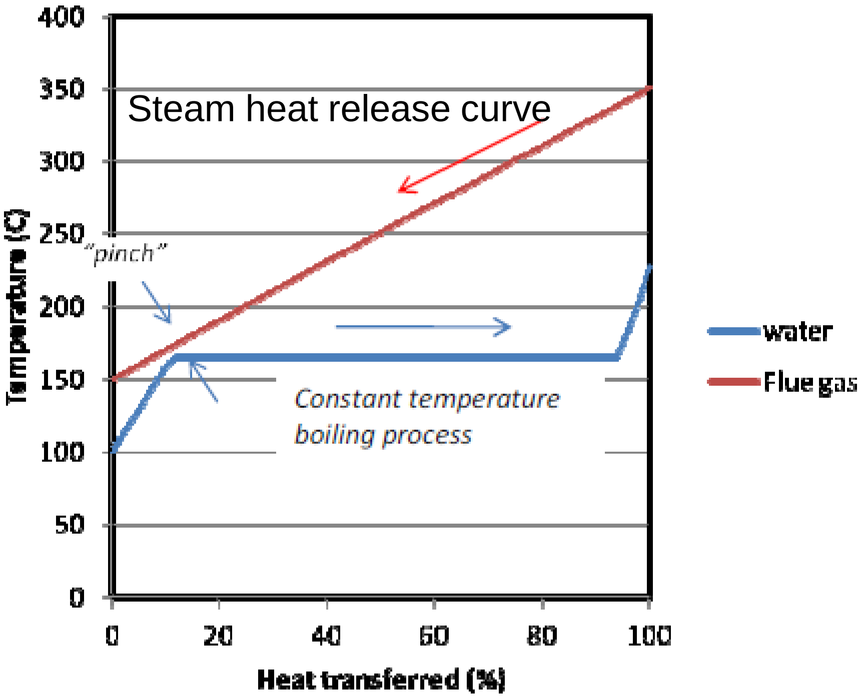
- 20 – 25 % first law efficiency
- Up to 10 % more efficient than ORC
- Heat Sources include Geothermal, exhaust gasses, industrial waste, solar, etc



Lou Qualls (ORNL)

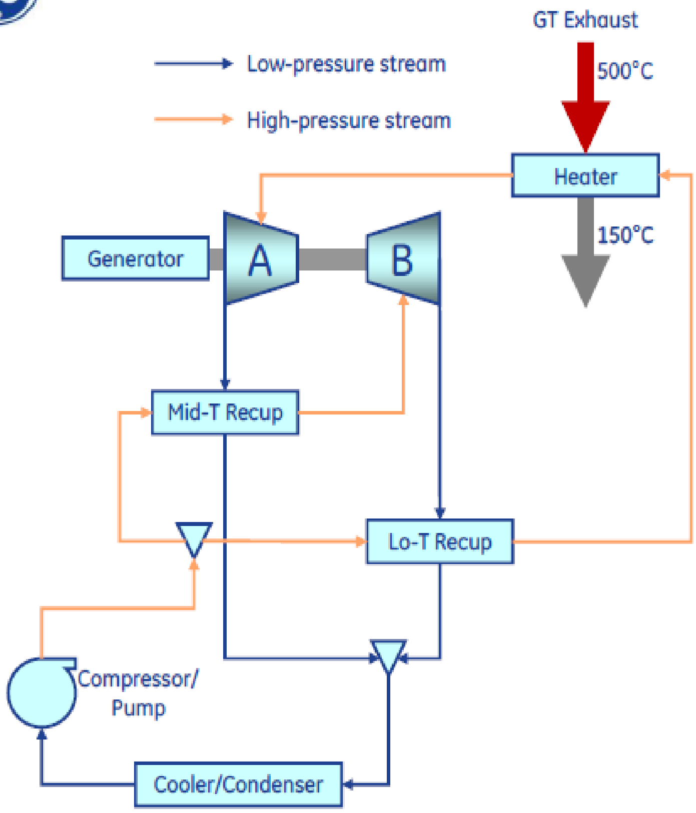
Exchanger application in SCO_2 Cycles



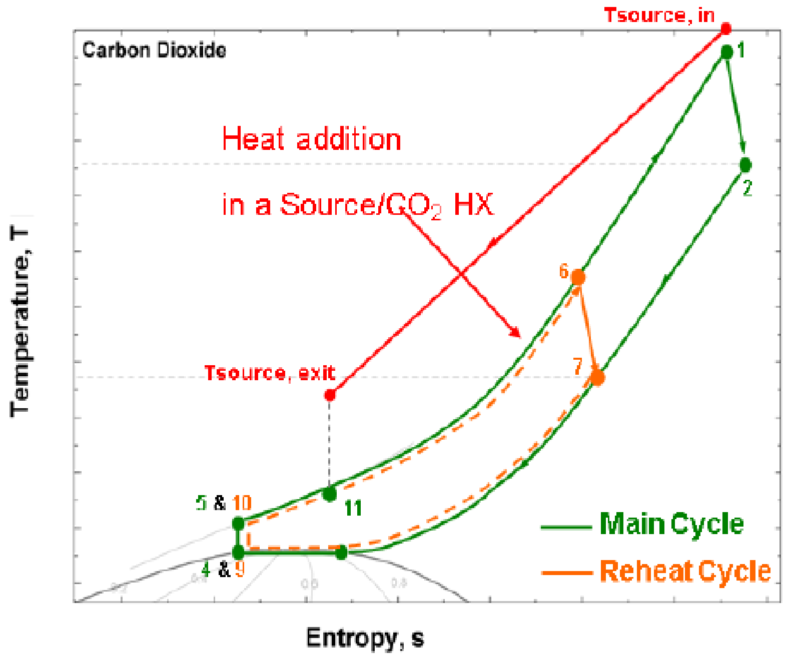


- Better heat recovery possible in SCO2 cycles with single phase exchangers
- Two phase boiling at constant temperature (steam cycles) limits close temperature approach (pinching)

Applications using SCO_2 Rankine Cycles

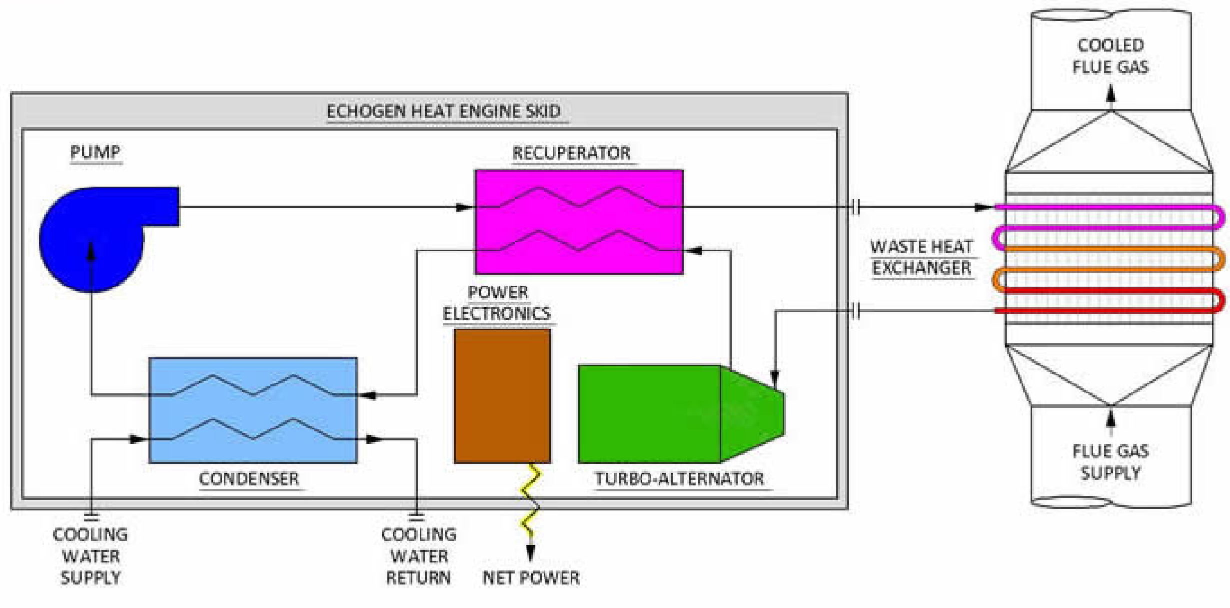


Courtesy of GE GRC (patent pending)



- 30% first-law efficiency
- Better utilization of exhaust energy
- 10% more power output compared to ORC
- Compact turbo-machinery with low footprint

Echogen EPS systems



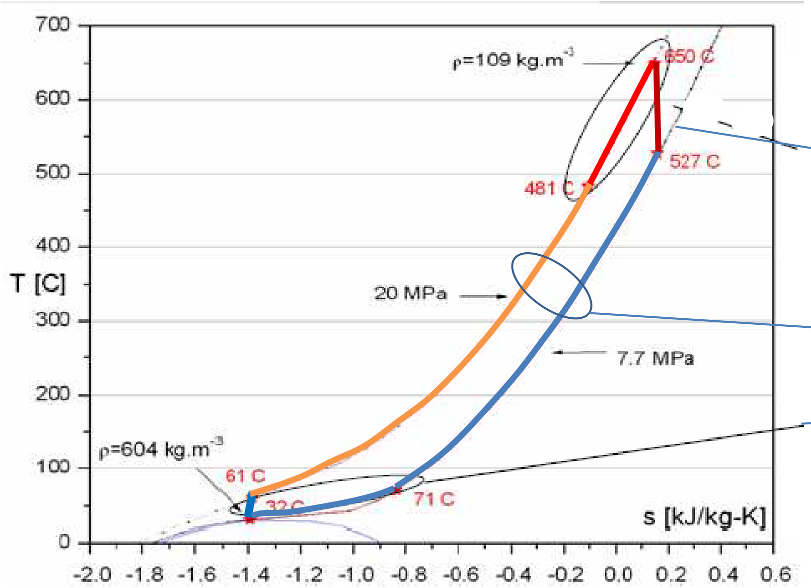
Echogen commercialisation

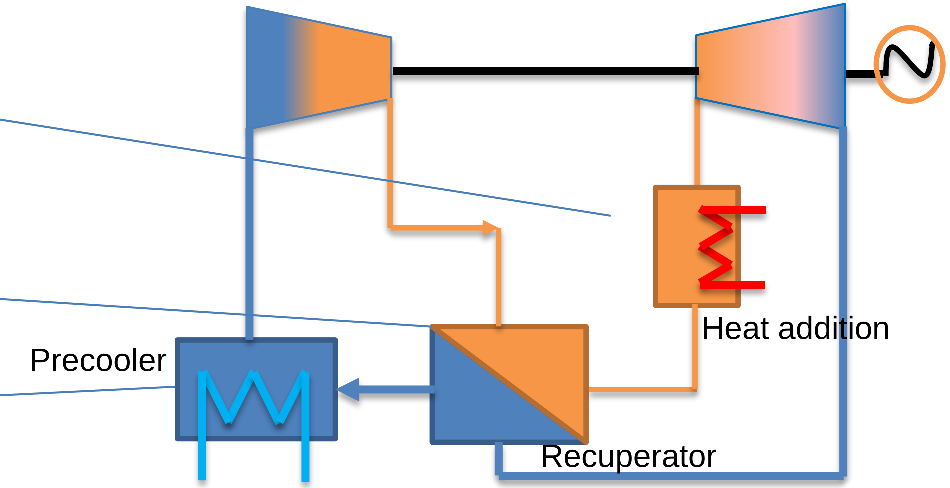
- Built and tested demonstration unit
- Since designed and built commercial scale system, EPS100 (6-8 MW)
  - Ongoing testing at Dresser Rand’s facility at Olean in New York
- Similar system, EPS 7 (400kW), currently in design for commercial introduction in 2014

Echogen used compact exchangers
$>300m^2$ heat transfer area
~13000kg
Core ~ 1.5 x 1.5 x 0.5 m

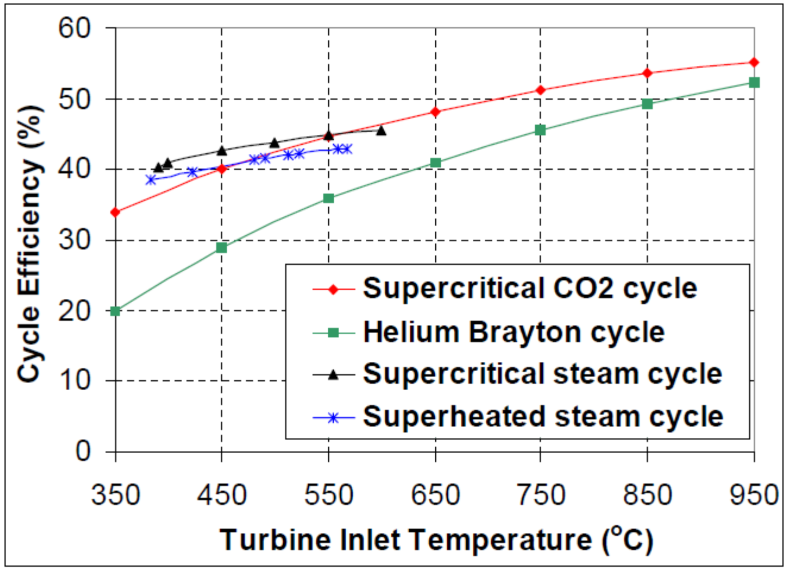
Comparable S&T:
$>850m^2$
~50000kg
Shell ~ 1.2m diameter x 12m length

Exchangers in SCO2 Brayton Cycles





- Better fuel-power conversion efficiency
- Require high turbine inlet temperatures for efficient operation
- Simple cycles are highly recuperative
- Compressive work takes significant portion of developed power

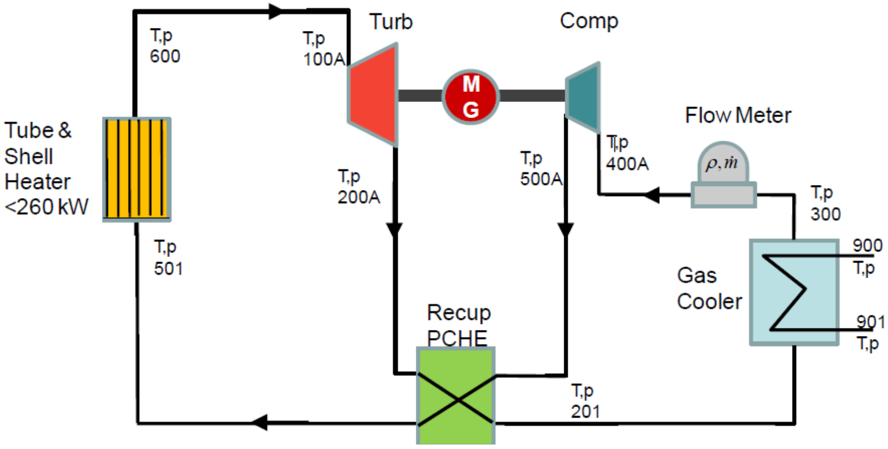


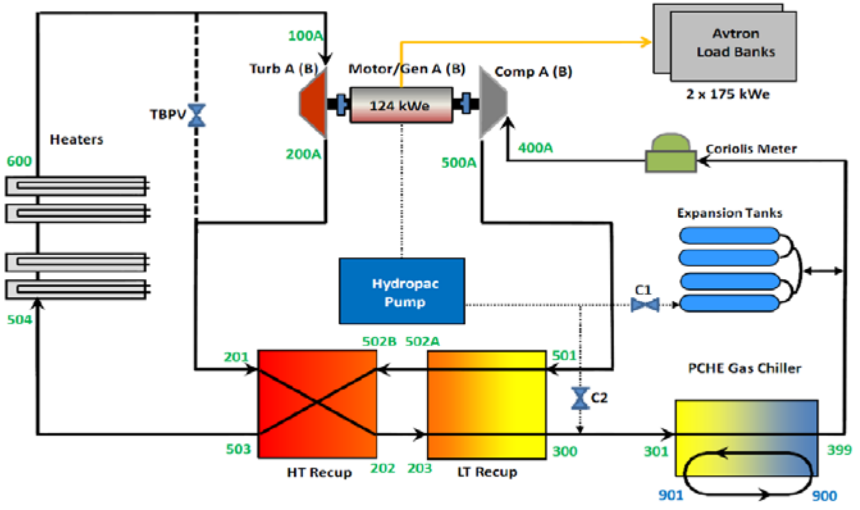
Exchangers that can be used in Brayton cycle include

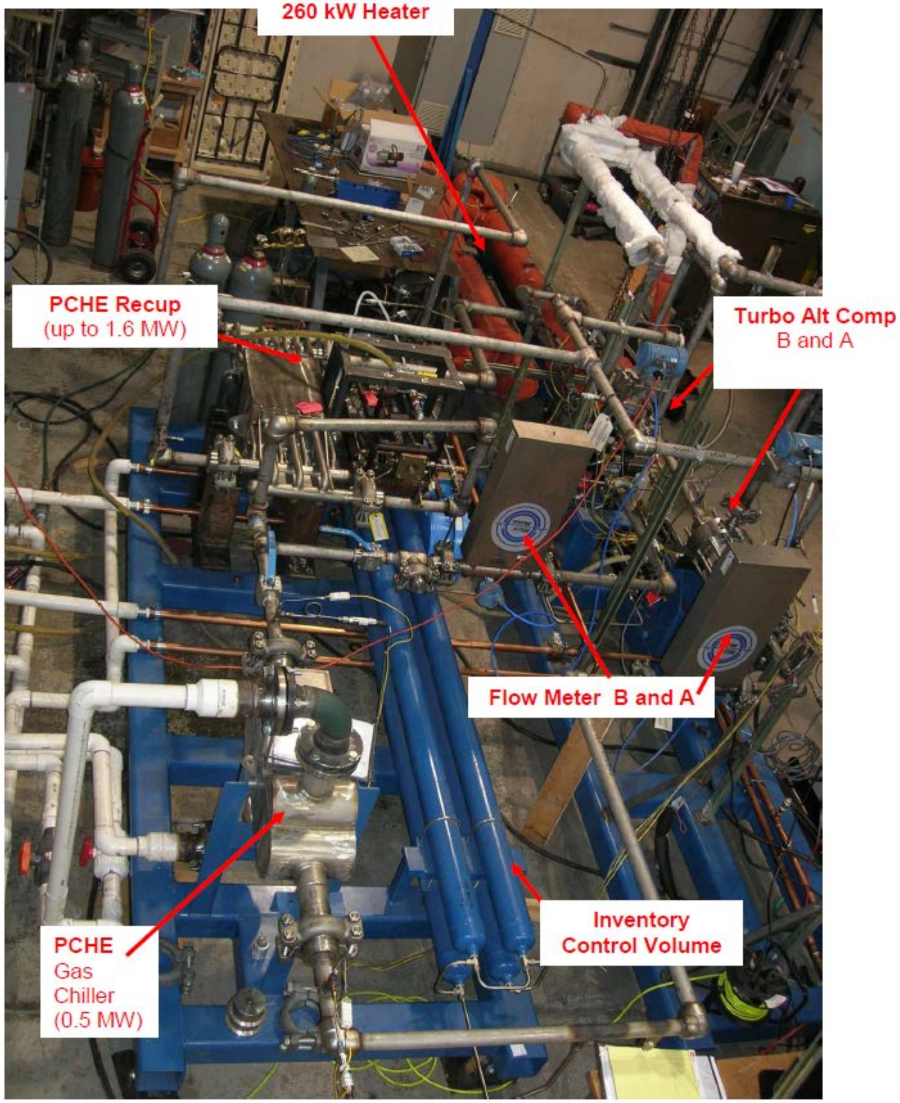
- Spiral wound exchanger
- Shell and tube
- Diffusion Bonded exchangers (plate fin and etched channels)
- Hybrid exchangers
- Finned tube and shell
- Plate and shell
- Porous media (metallic foam) exchangers

Sandia / Barber Nichols Inc.

Sandia has built and tested simple and recompression sCO2 test loops



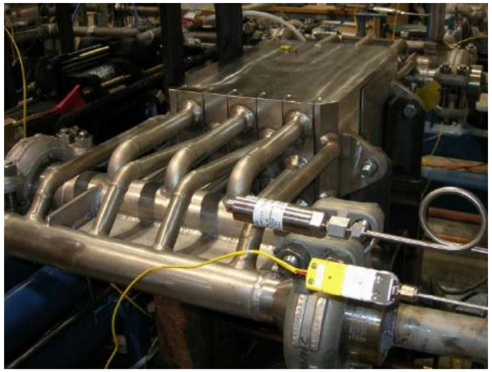




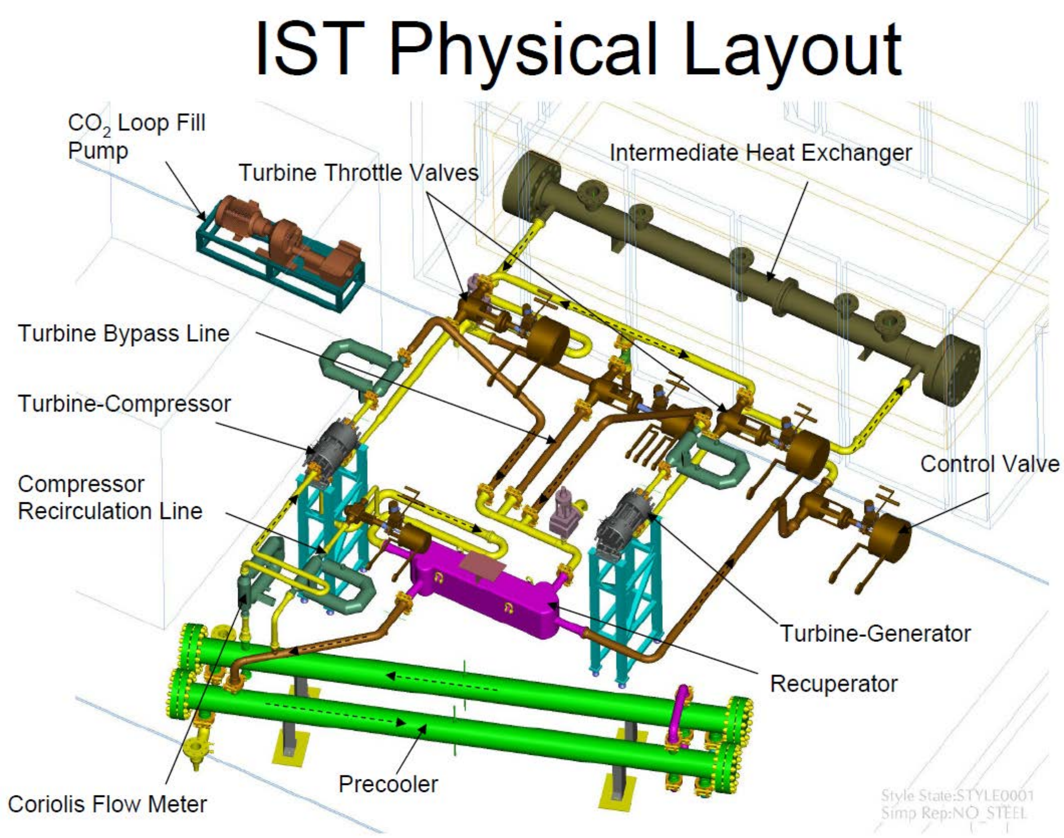
Wright; Conboy

Sandia Heat Exchangers used

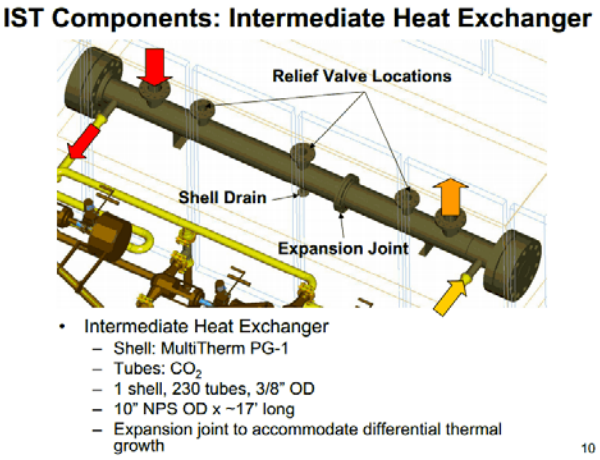
- HT Recuperator
  - 2.27 MW
  - 482°C (900°F)
  - 17.24 MPa (2500 psig)
- LT Recuperator
  - 1.6 MW
  - 454°C (849°F)
  - 17.24 MPa (2500 psig)
- Gas Chiller
  - 0.53 MW
  - 149°C (300°F)
  - 19.31 MPa (2800 psig)
- 6 ‘Shell and Tube’ heaters
  - U tubes contained resistance wire heaters



Bechtel – Integrated Test System



IST Physical Layout



IST Components: Intermediate Heat Exchanger

- Intermediate Heat Exchanger
  - Shell: MultiTherm PG-1
  - Tubes: CO_2
  - 1 shell, 230 tubes, 3/8" OD
  - 10" NPS OD x ~17' long
  - Expansion joint to accommodate differential thermal growth

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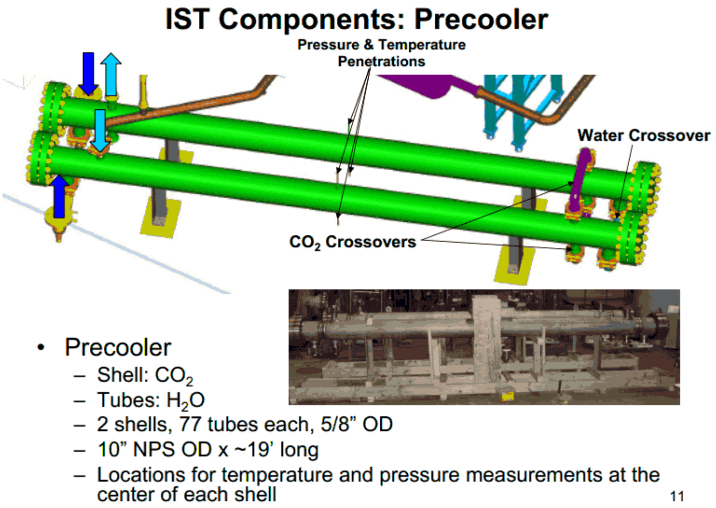

IST Components: Precooler

- Precooler
  - Shell: CO_2
  - Tubes: H_2O
  - 2 shells, 77 tubes each, 5/8" OD
  - 10" NPS OD x ~19' long
  - Locations for temperature and pressure measurements at the center of each shell

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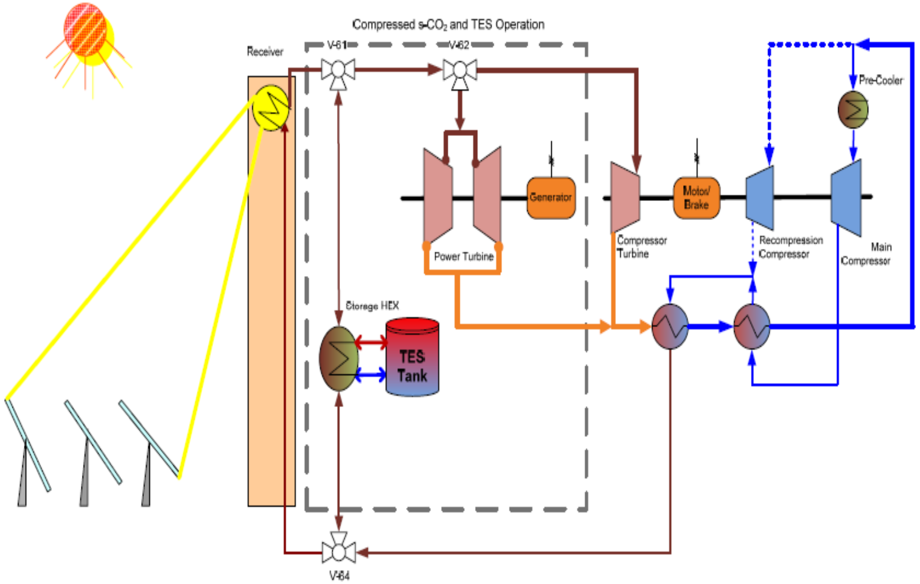
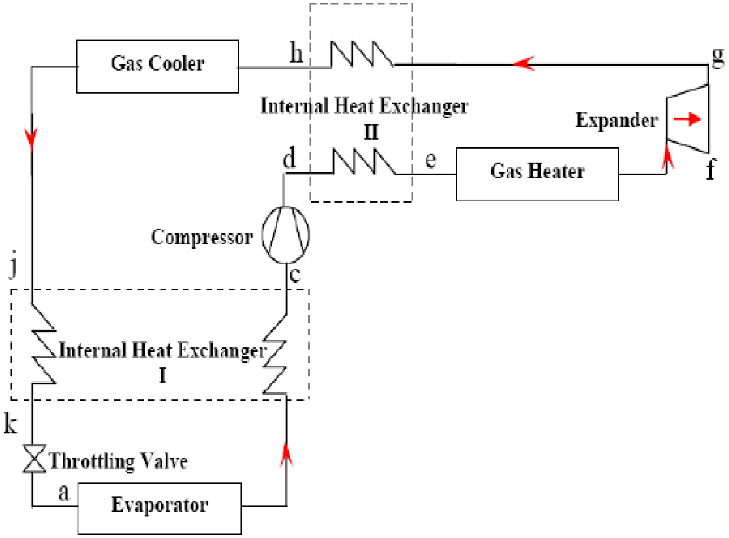
HOFFMAN
Process, Inc.

Other Advanced SCO2 power cycles include

CSP closed-loop recompression Brayton cycle with thermal storage

Cooling and power Combined cycles





Modular power tower design

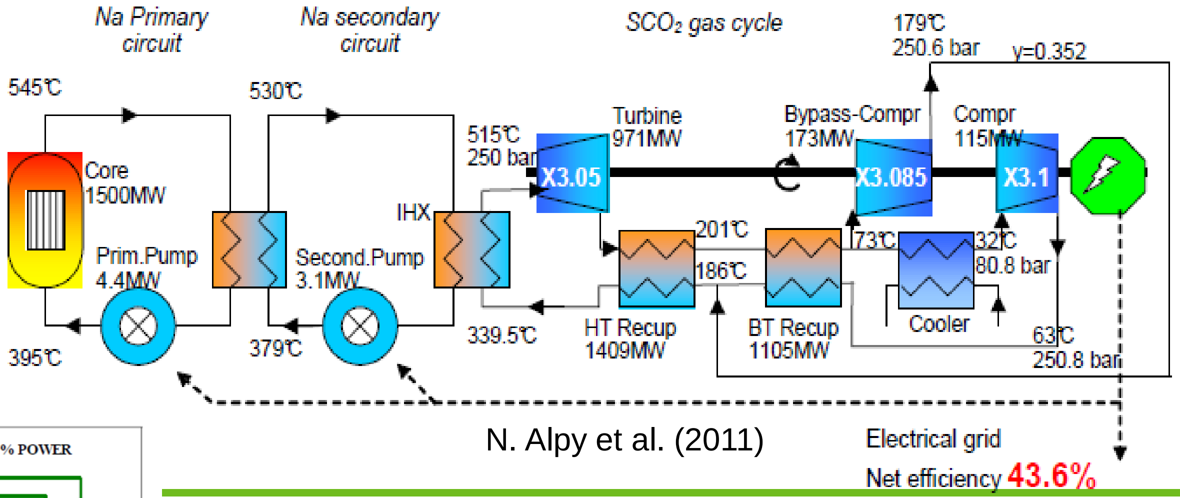
Tri-generation if the gas cooler provides heating service

The lower thermal mass makes startup and load change faster for frequent start up/shut down operations and load adaption than a HTF/steam based system

Ma and Turchi, (2011)

S-CO2 Brayton Power conversion for SFRs

CEA Astrid test program- research shows significant efficiency increase using SCO2 (43.6%) compared to existing (180 bar) N2 cycle (37.8%)



N. Alpy et al. (2011)

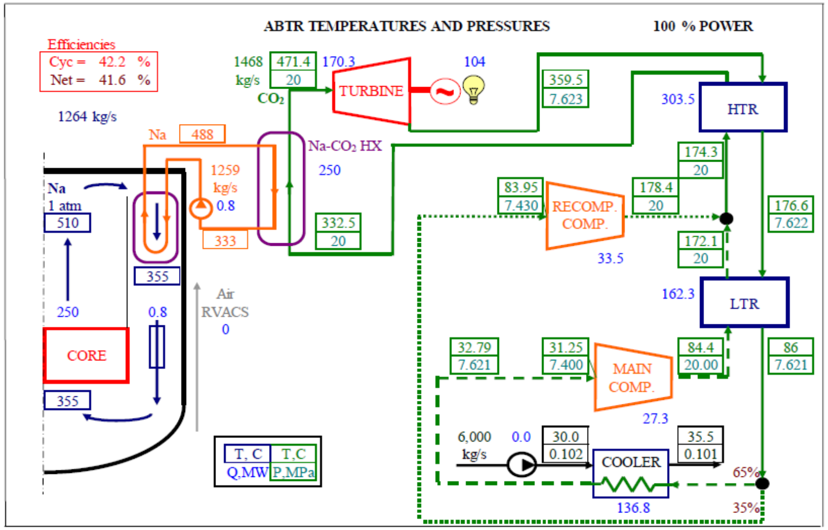


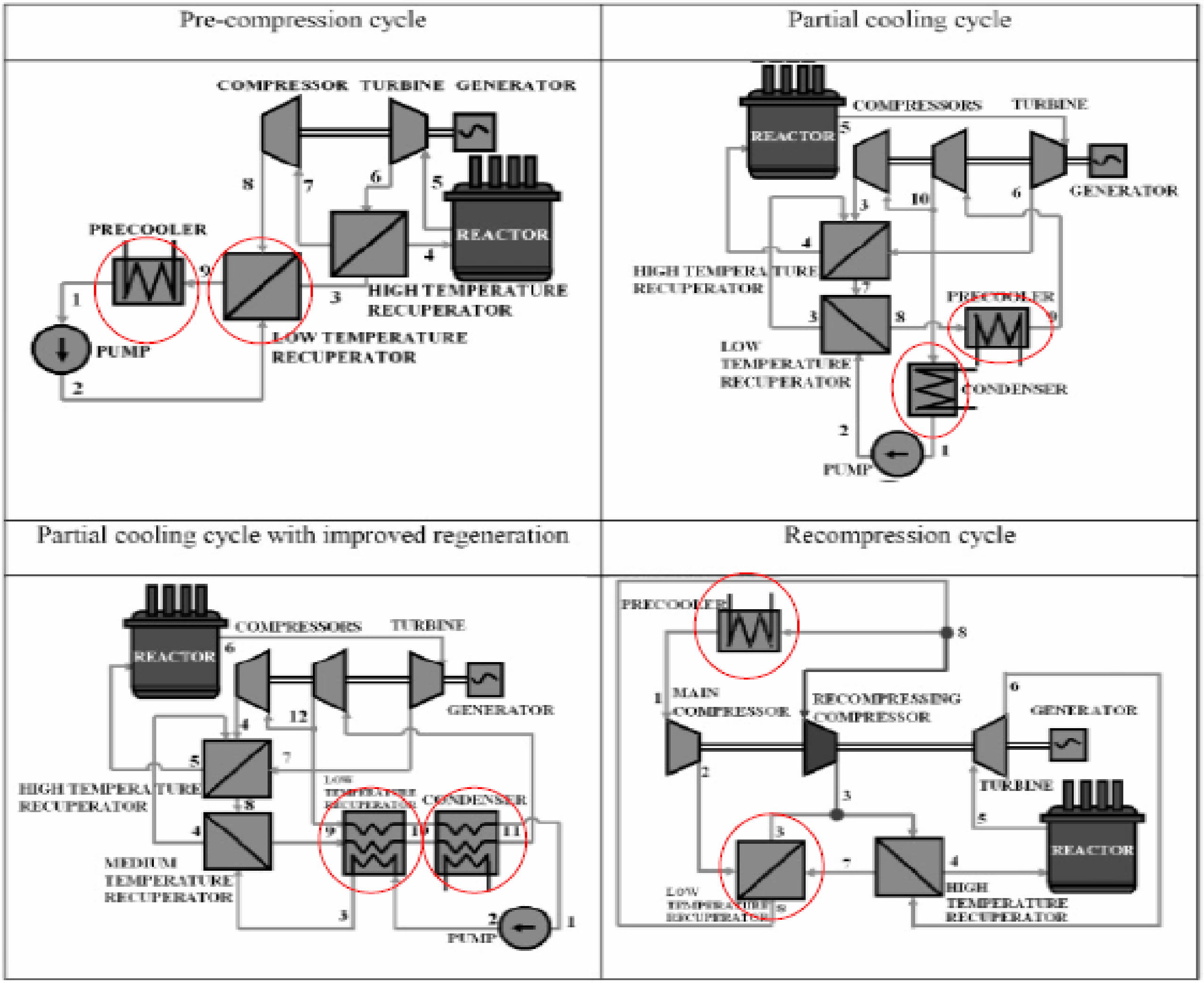
Figure 21. S-CO₂ Cycle Performance with "Ideal" Heat Exchangers.

Advanced Burner Test Reactor (ABTR) concept design study by ANL.

Potential efficiency increase to 45%

ANL-GenIV-103 report

Future modifications to advanced cycles will require more heat exchanger applications



Pre-compression cycle

Partial cooling cycle

Partial cooling cycle with improved regeneration

Recompression cycle

(Dostal et al. 2006)

System Optimisation for Heat Exchangers

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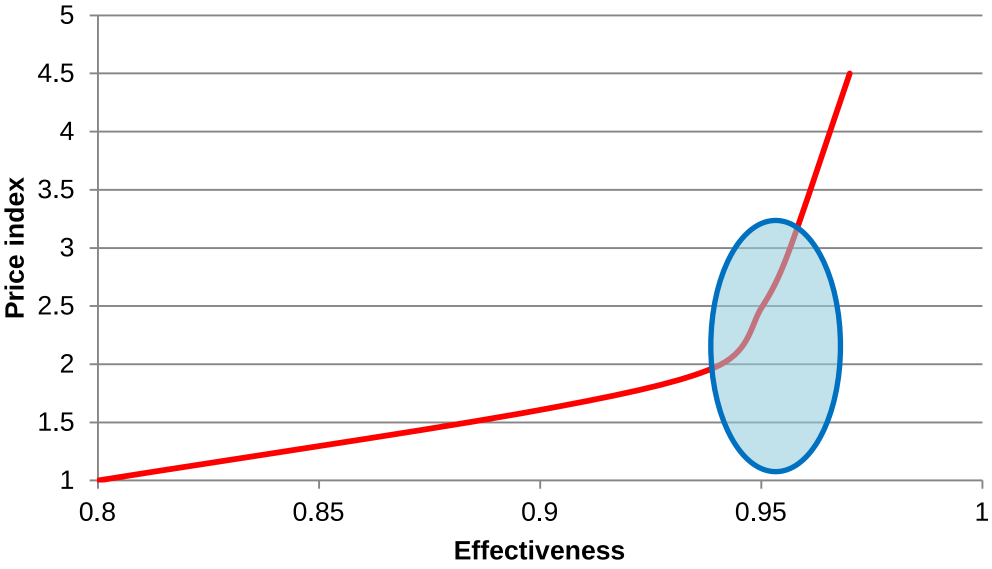
Heat exchanger design considerations

- Plant efficiency vs CAPEX
    - Close temperature approach requires high effectiveness recuperators
    - Higher design temp requires high nickel alloy
- Large property changes require sensitivity checks
    - Operating conditions
    - Pressure levels
- Off design points including turn-down conditions needs to be analysed for avoiding pinch point and reversal

Heat exchangers currently form a large part of the overall system cost

CAPEX vs OPEX studies are required to find optimum operating point of the system

- Temperature approach and pressure drop both greatly affect price

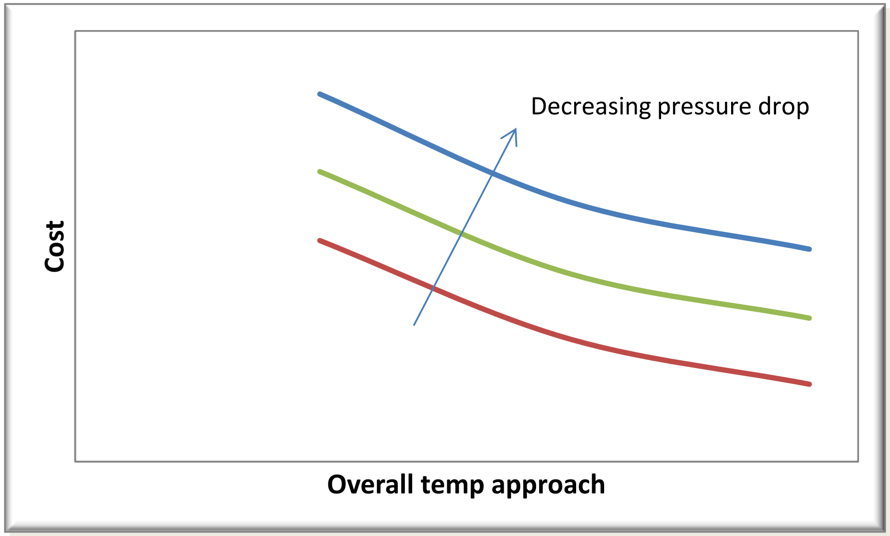


$$Eff = 1 - \frac{\Delta T}{T_{hi} - T_{ci}}$$

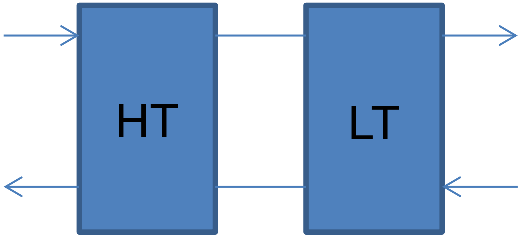
Where ΔT = minimum temperature approach

Pinch point varies per technology type. Graph shown for PCHE.

Optimum point varies depending on process conditions and technology type used

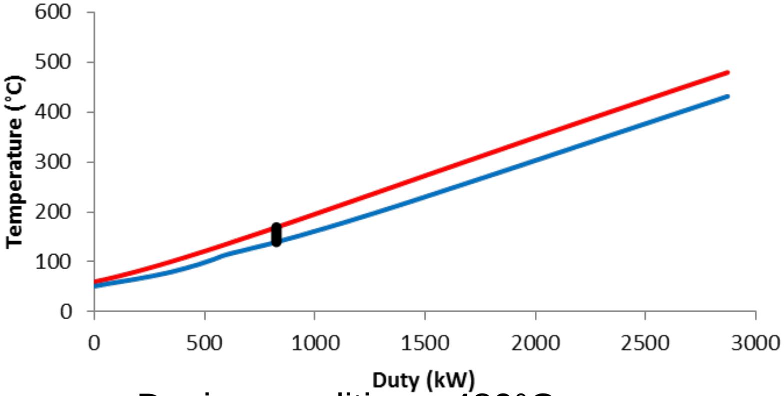


Design Cases need careful consideration

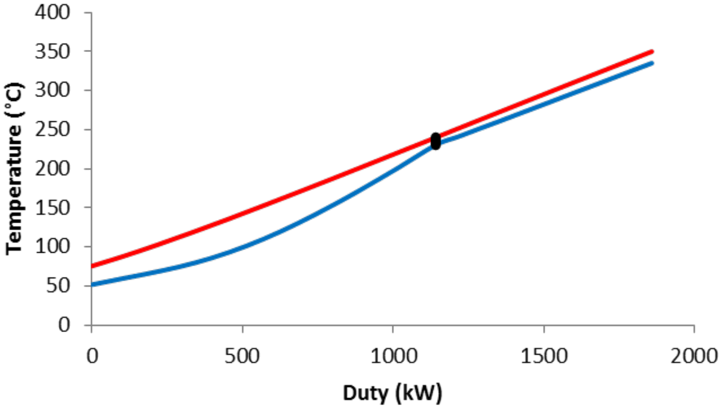


Reducing the inlet temperature away from the designed operating temperature can drastically change heat curve.

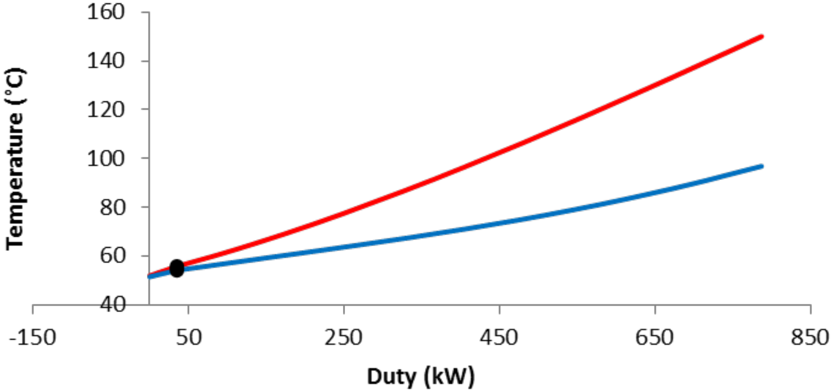
If lowered to much will cause pinch point in HT exchanger. Leaving LT exchanger redundant.



Design conditions: 480°C Inlet



350°C Inlet



150°C Inlet

HEXs suited for s-CO2 applications

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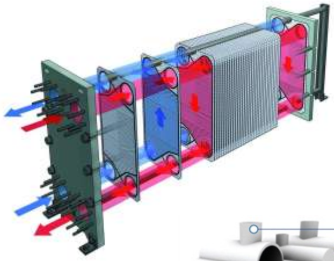
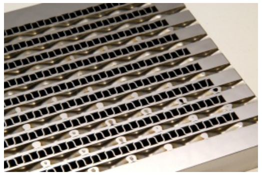
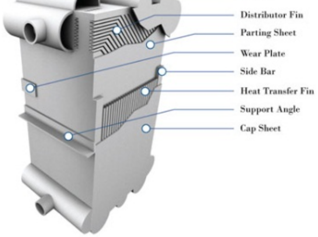
Exchanger Categories

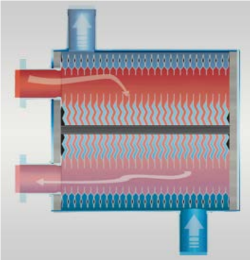
Shell and Tube

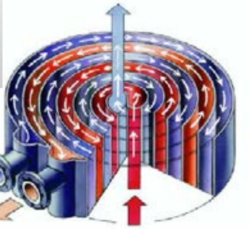
Compact











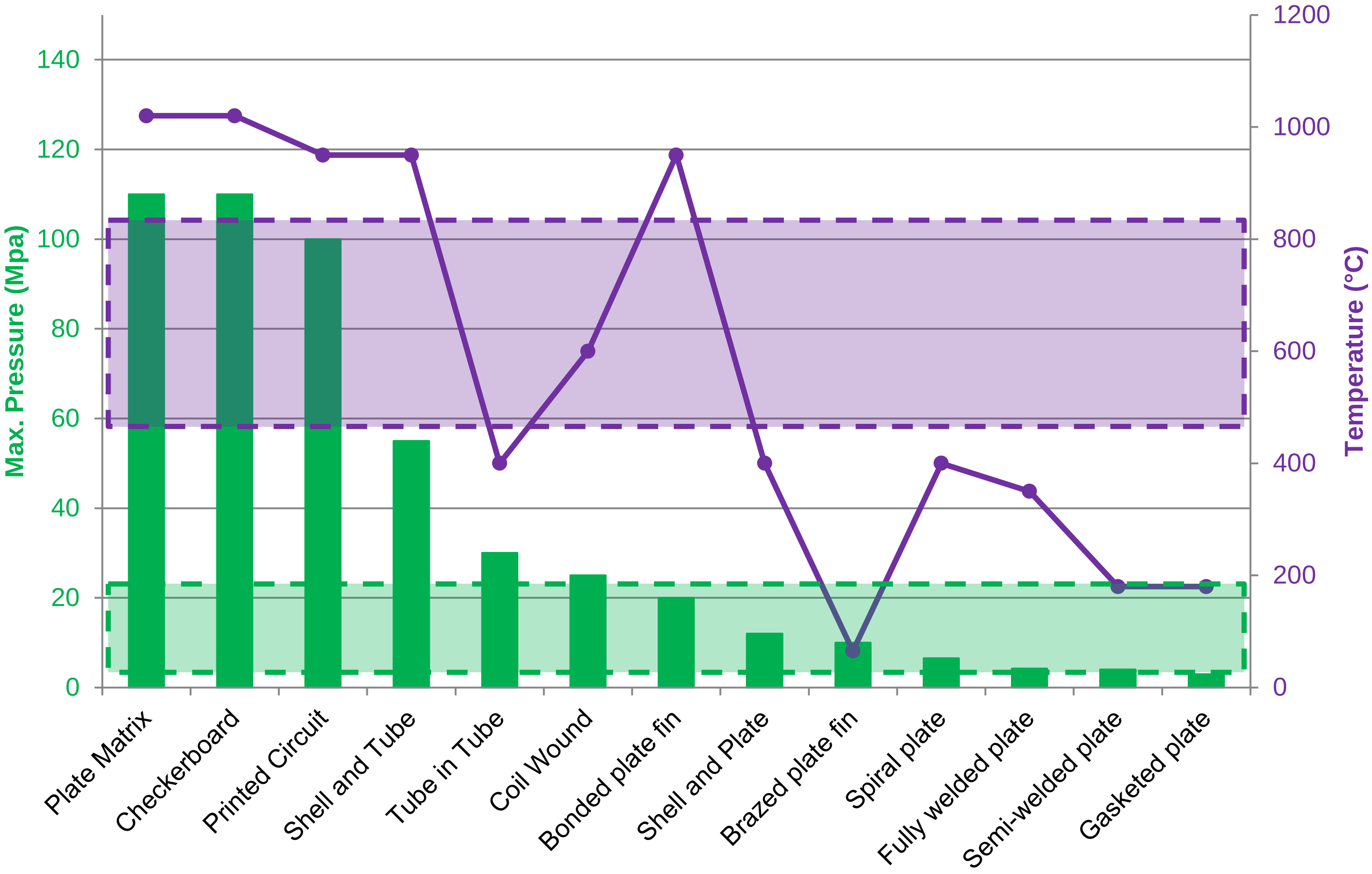
Air Cooled

General Overview

Exchanger type	Advantages	Disadvantages
Shell & Tube	- Most commonly available - Wide range of design conditions - Versatile in service	- Lower thermal efficiency - Subject to vibration issues - Large overall footprint
Compact	- Low initial purchase cost - Multiple configurations available - High thermal efficiency - Small overall footprint - Wide range of design conditions - High mechanical integrity - Thermo-mechanical strain tolerance	- Low mechanical integrity - *Small flow channels** - Single source (mfg)

*Also an advantage

Temperature and Pressure ranges of different Heat Exchanger types

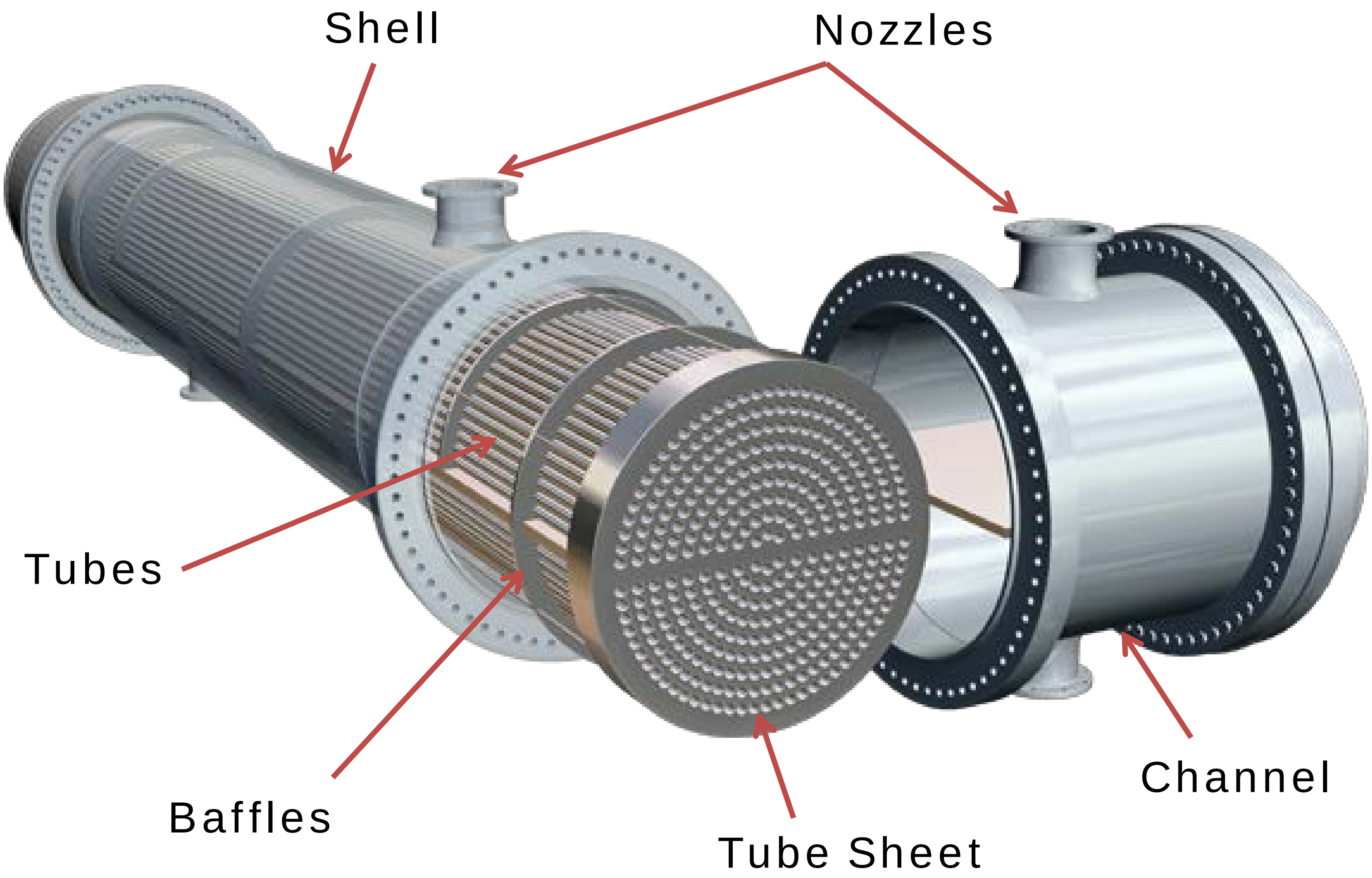


Data gathered from heat exchanger manufacturers websites. Note temperature and pressure are listed as separate items, it is not normally possible to achieve both these values together.

Shell & Tube

Source: [1]

Main Components



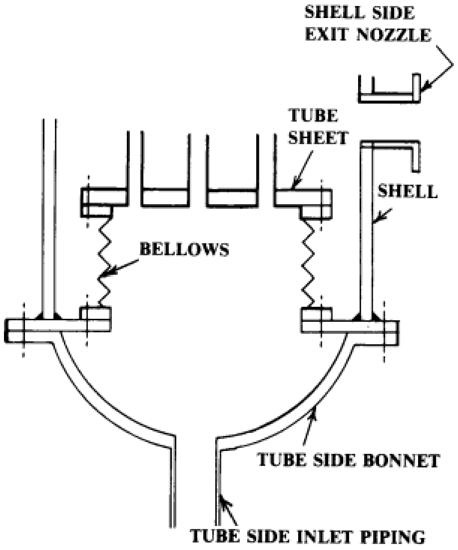
Source: [2]

Spiral Wound

- Components/construction
  - Spiral tube bundle
  - Tube spacers
  - Headers and piping to tubes
  - Shell
  - Headers and nozzles
  - Centre pipe (Mandrel)

Design considerations for sCO2 application

- High Temp - Thermal Stress
  - Expansion Joint
  - Internal Bellows
  - U-Tube design
  - Floating Head
- Temperature approach
  - Baffles
  - Multiple Shells



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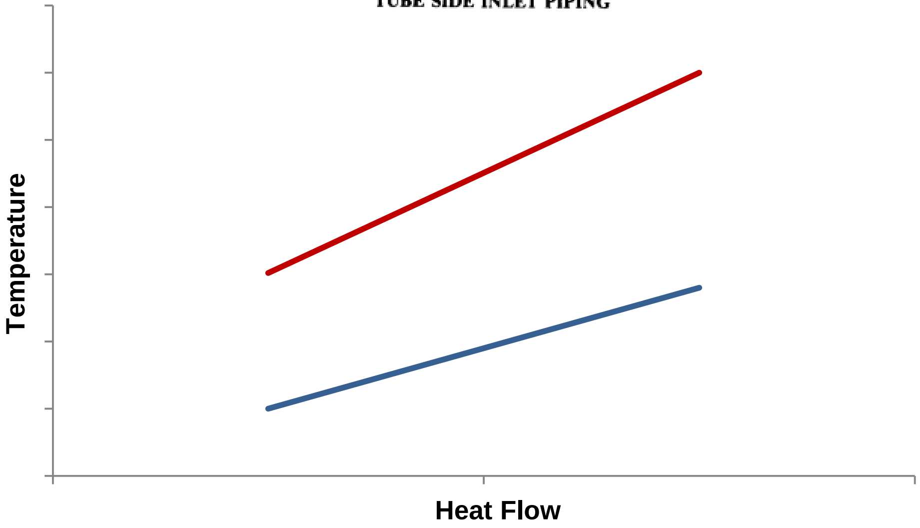
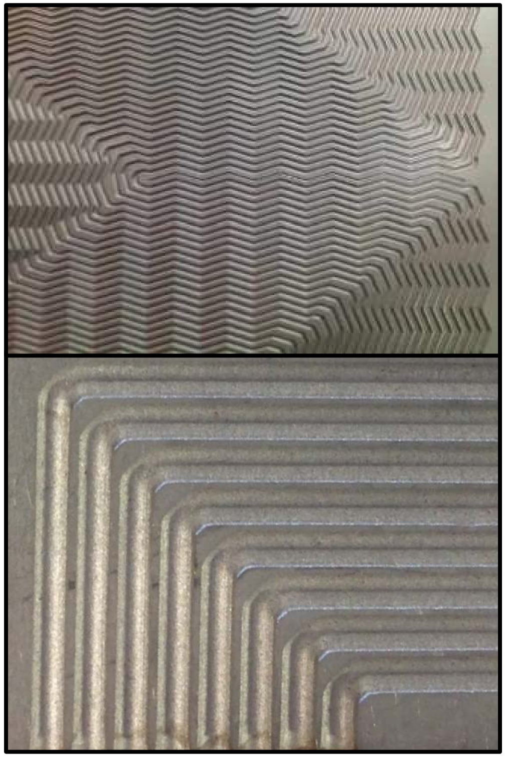
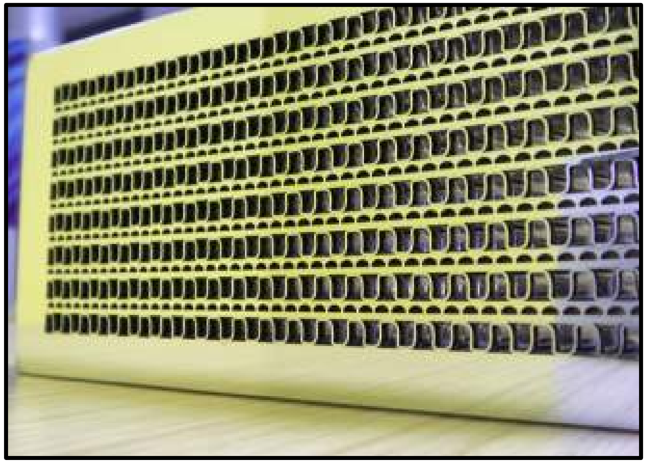


Heatric PCHE



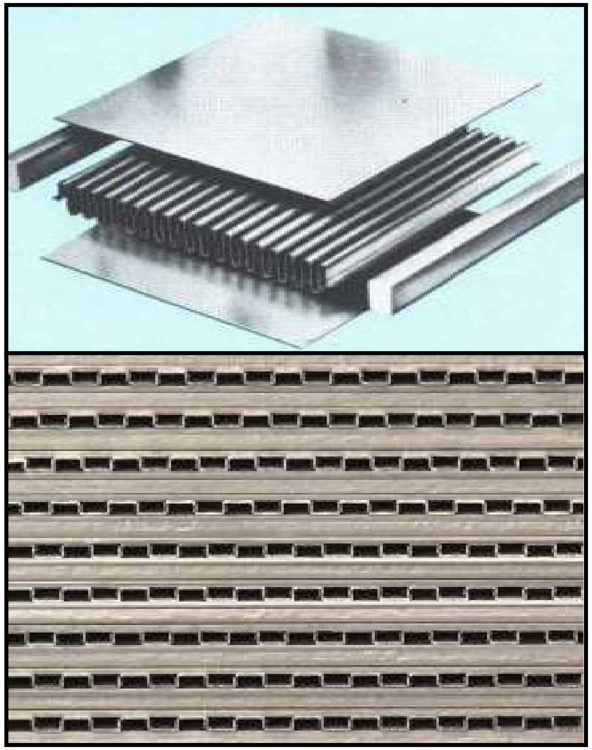
PCHE

Printed Circuit Heat Exchanger



H^2X

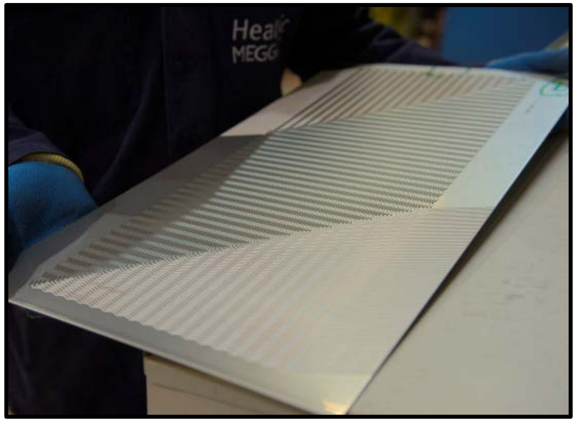
Hybrid

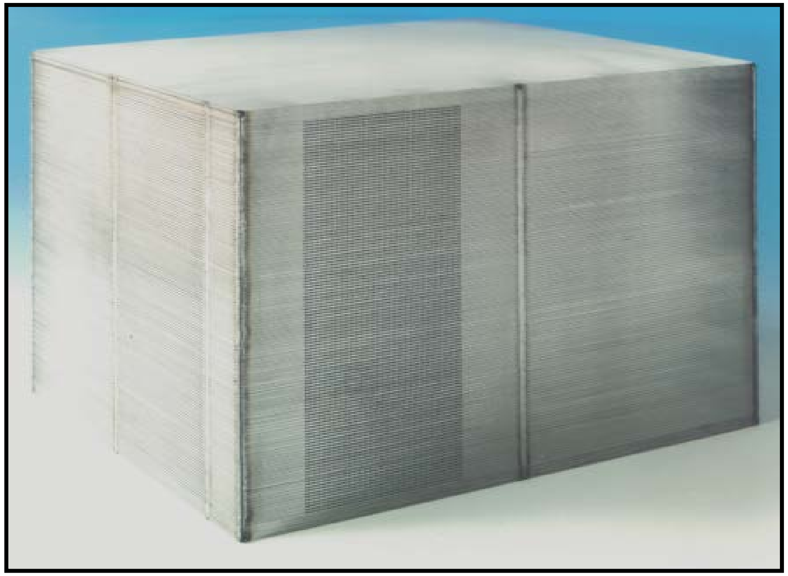


FPHE

Formed Plate Heat Exchanger

Main Components



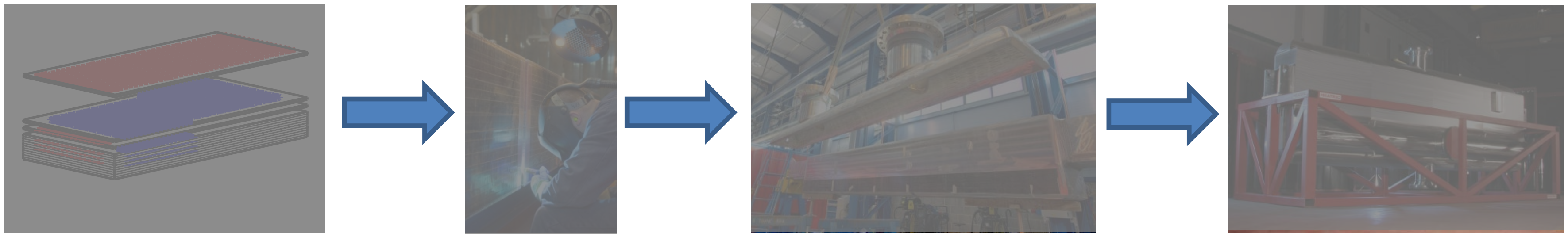


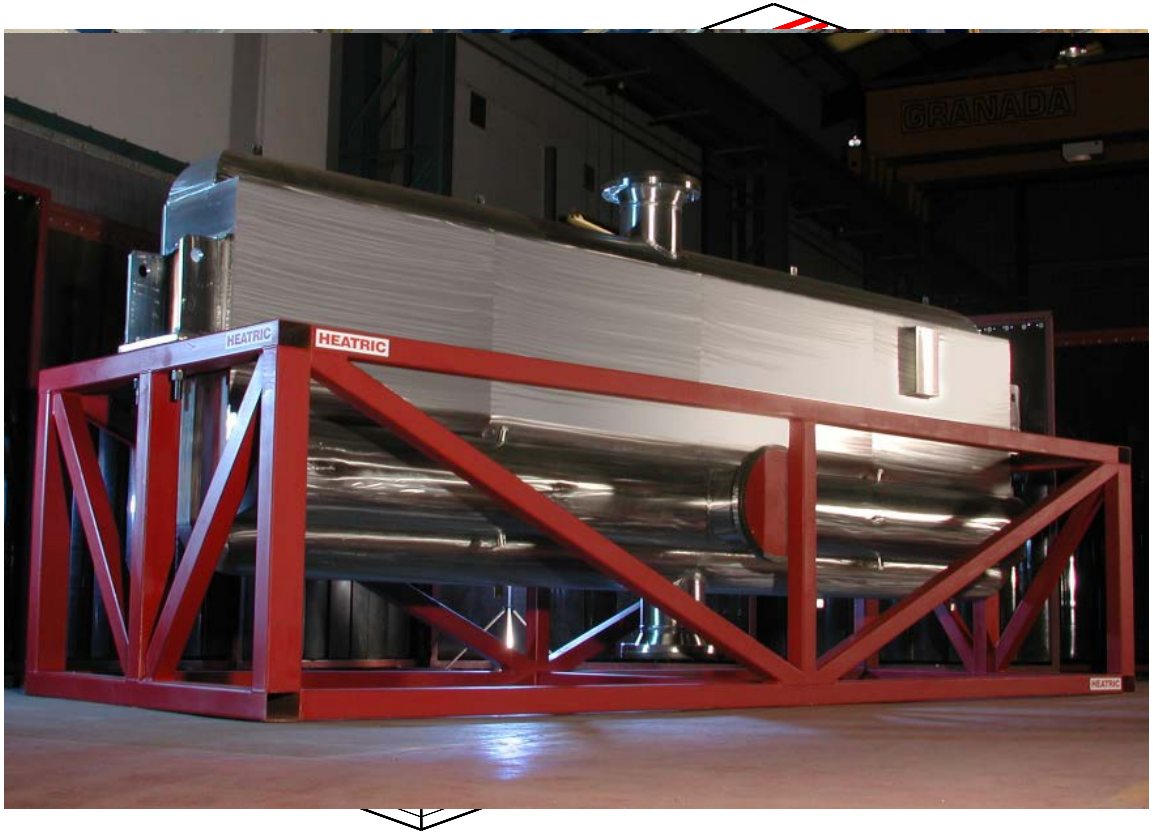
Diffusion
bonded core

Etched plates
Or
Formed plates

Headers,
nozzles,
flanges

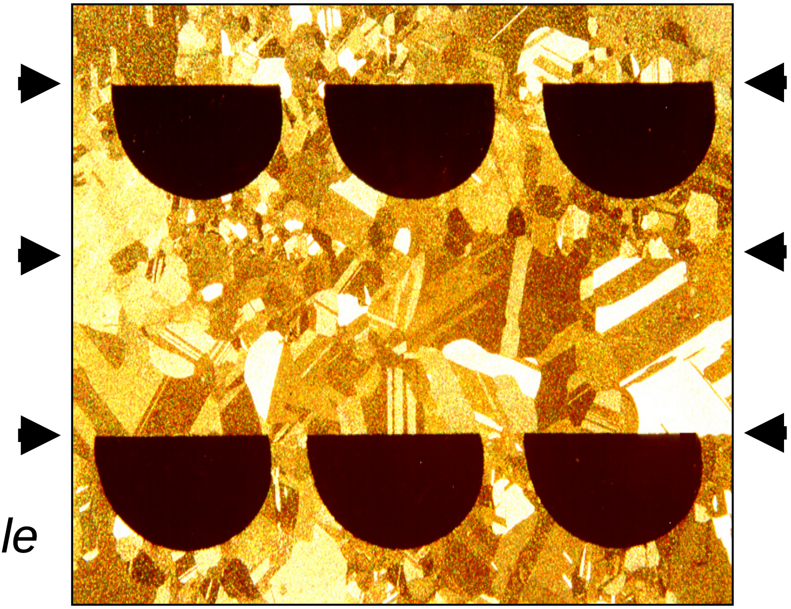
Construction





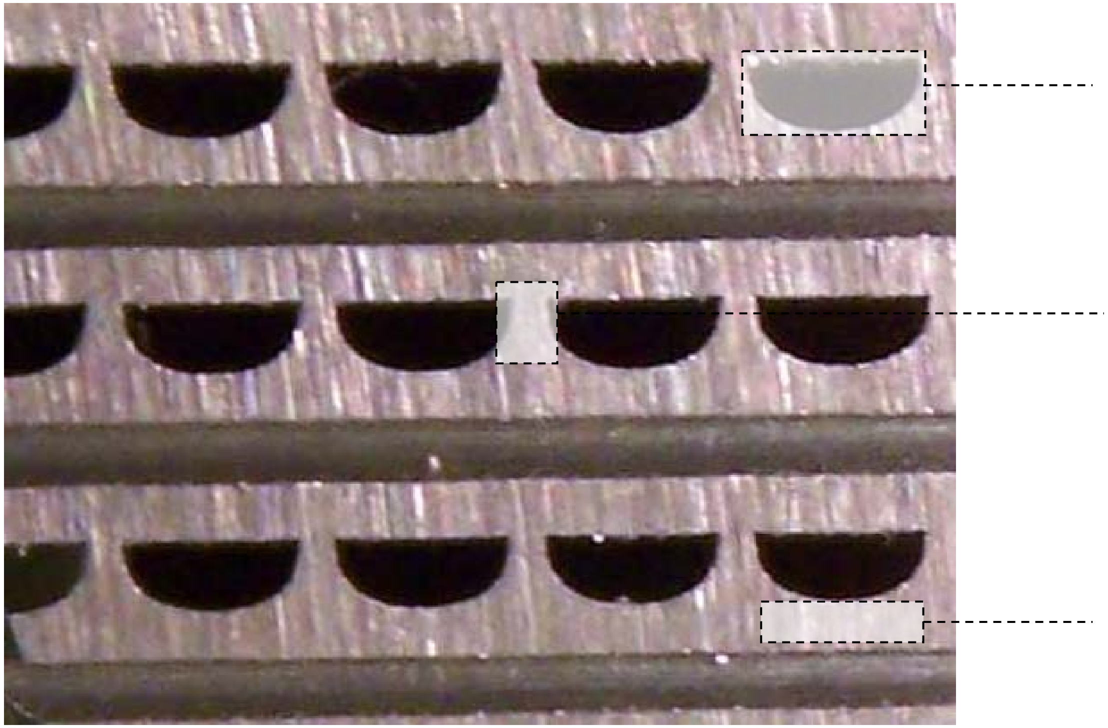
1. Stack and Diffusion Bond Core
2. Block to block joints
3. Assemble headers, nozzles and flanges
4. Weld headers, nozzles and flanges to core

Core Details



Current Typical Dimensions
Channel Depth – 1.1 mm
Plate Thickness – 1.69 mm
Individual core block – 600 x 600 x 1500 mm
Total unit length – 8500 mm
Hydraulic Diameter – 1.5 mm

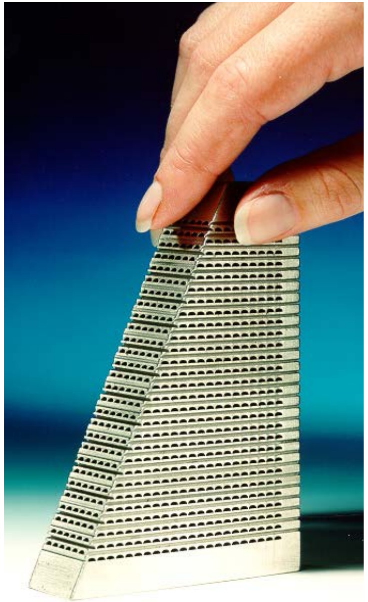
Cores are bespoke designed and values are variable depending on thermal and hydraulic requirements



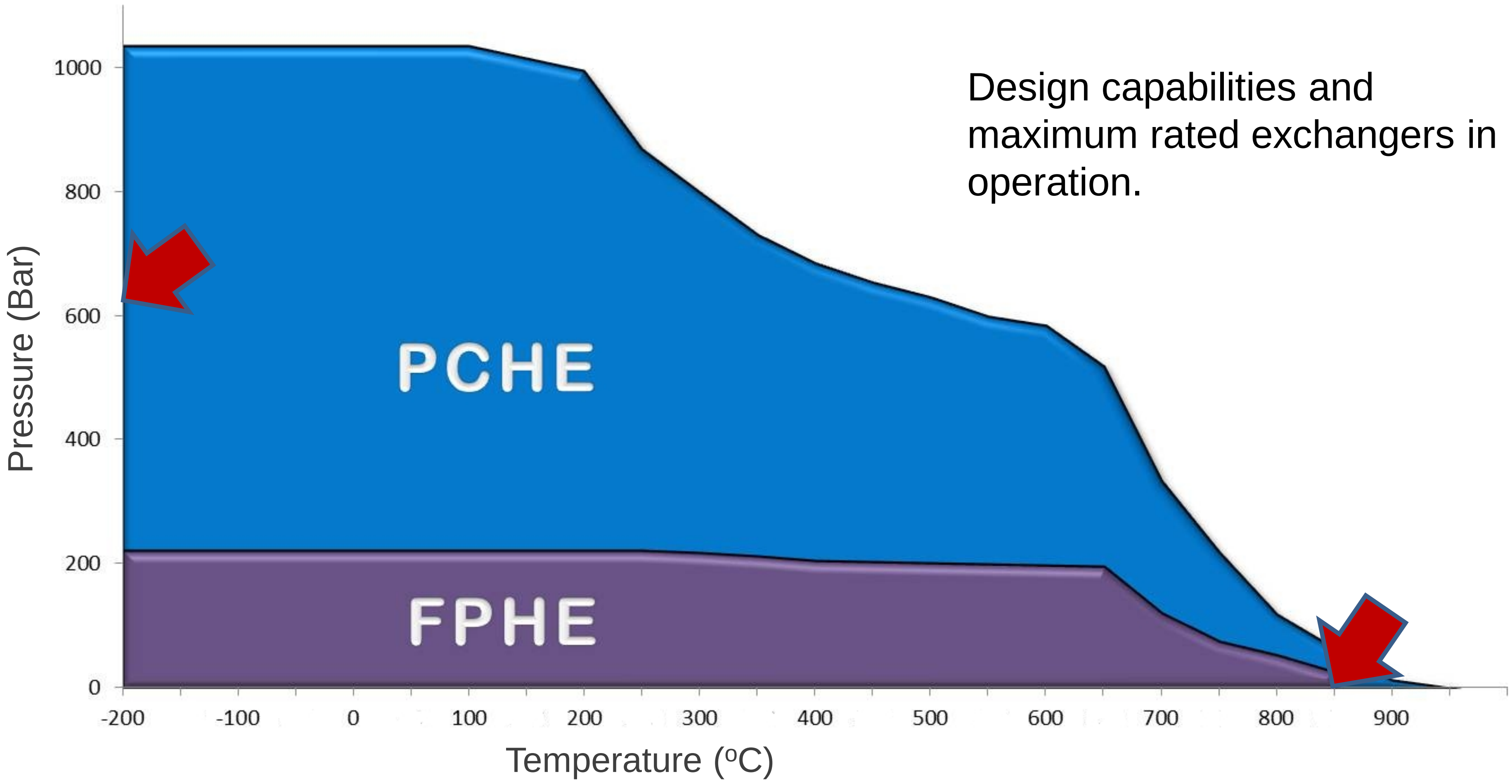
Channel/Passage

Ridge

Wall



Operating Conditions



Design capabilities and maximum rated exchangers in operation.

Heat Exchanger Types

Continued

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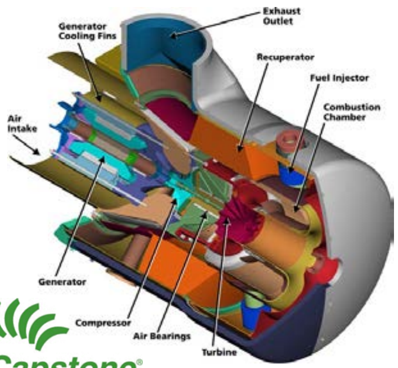
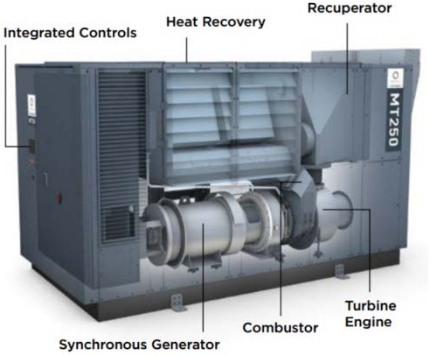
Plate-Matrix Heat Exchangers – An Overview



Capstone®

(30, 65, and 200 kW)

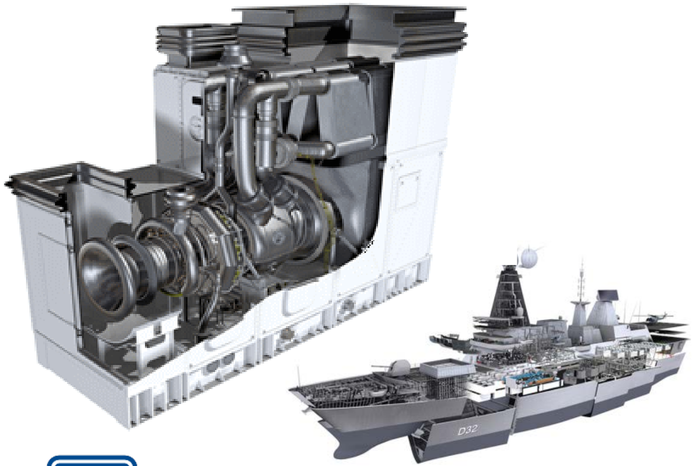


FLEXENERGY

(250 and 333 kW)

IR Ingersoll Rand

(70 and 250 kW)



ROLLS ROYCE

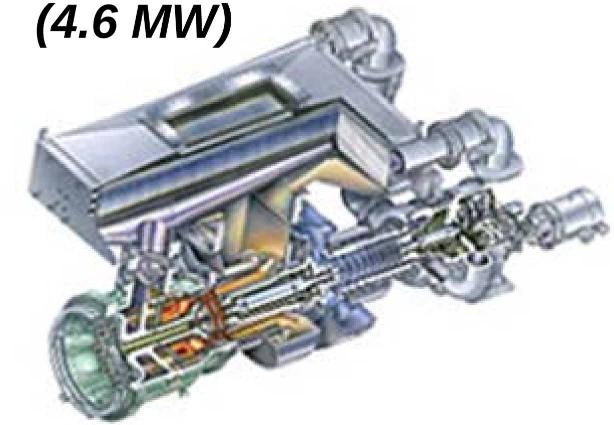
Rolls-Royce®

WR-21 (25.2 MW)

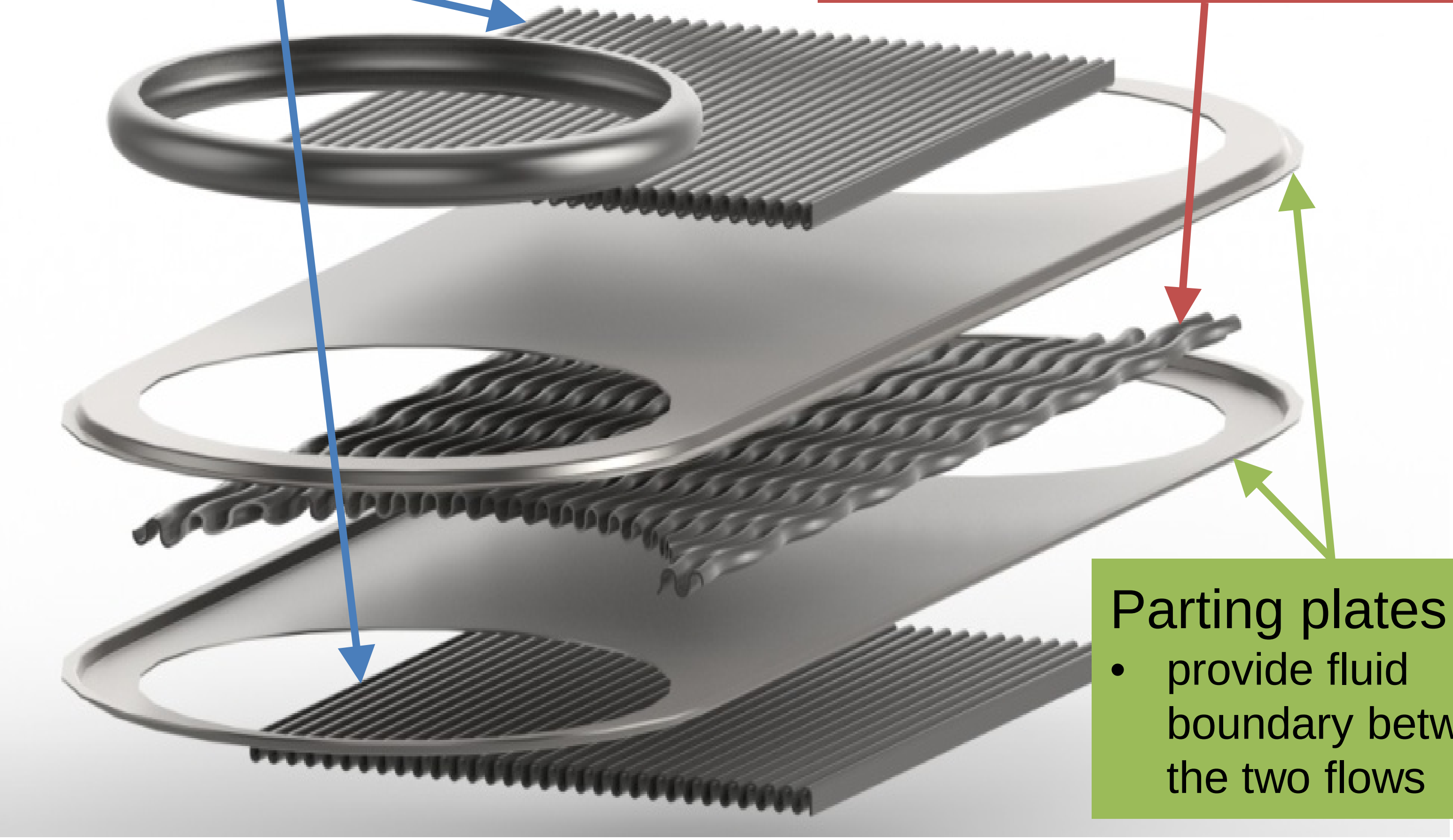
Solar® Turbines

A Caterpillar Company

Mercury-50
(4.6 MW)



The Plate-Matrix Unit Cell



External low-pressure matrices

- Enhances the heat transfer of the low-pressure fluid as it flows between adjacent unit cells

Internal high-pressure matrix

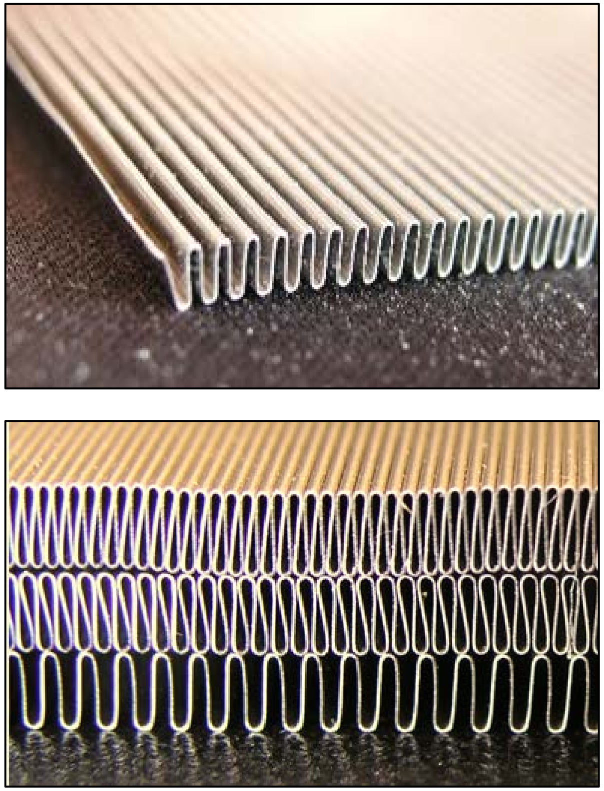
- Enhances the heat transfer of the high pressure fluid as it flows between the two parting plates
- Can serves as structural features for high-pressure (sCO_2) applications

Parting plates

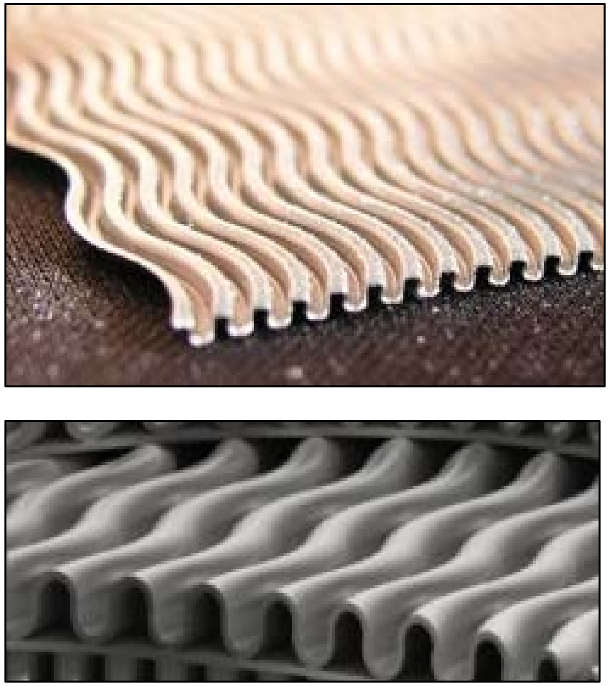
- provide fluid boundary between the two flows

Heat Transfer Matrices

Straight Fin



WavyFin



Wire Mesh

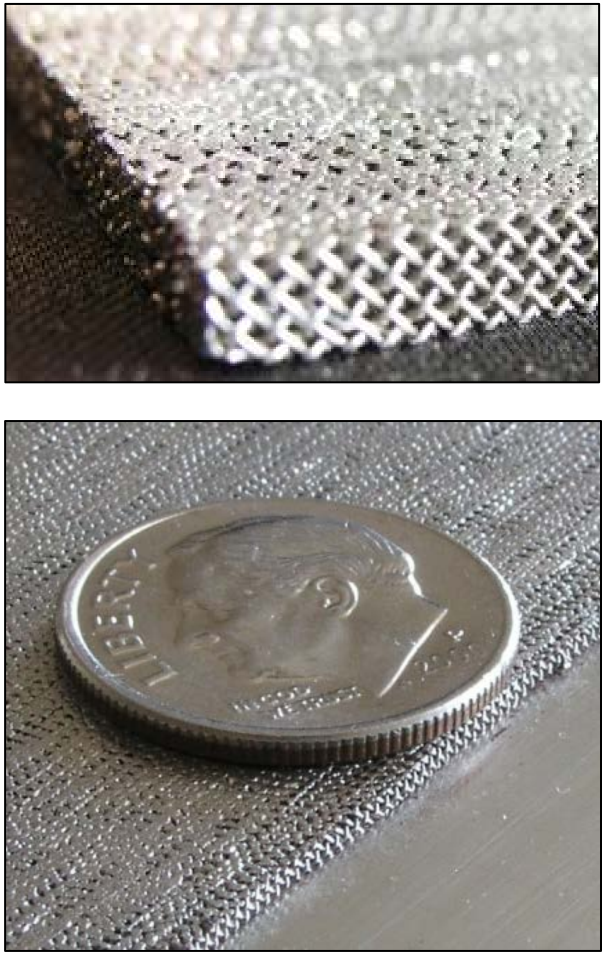
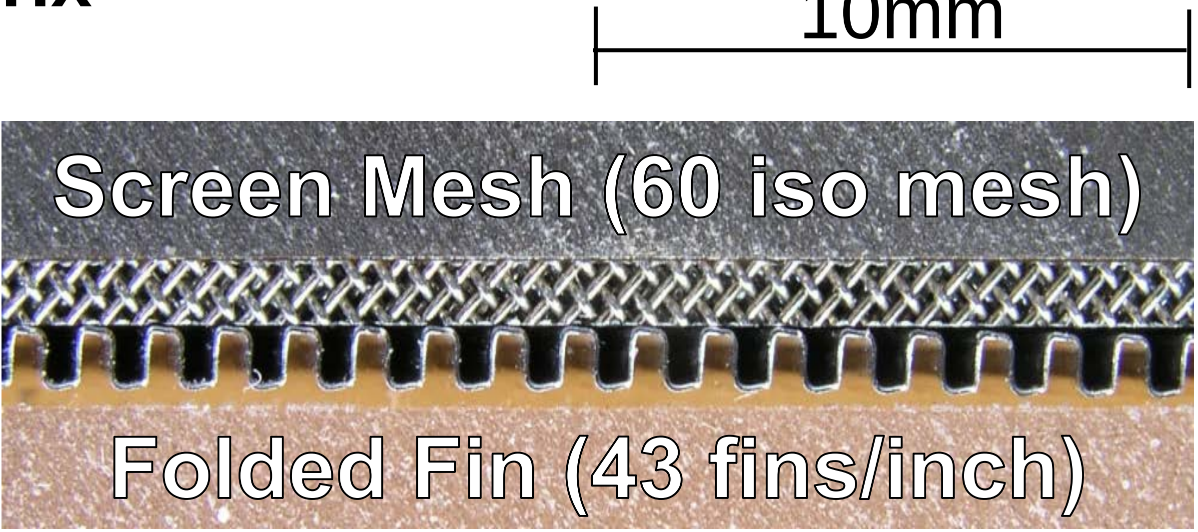


Plate-Matrix Heat Exchangers

Choosing a Matrix

- Cost
- Mass
- Footprint
- Size (Volume)



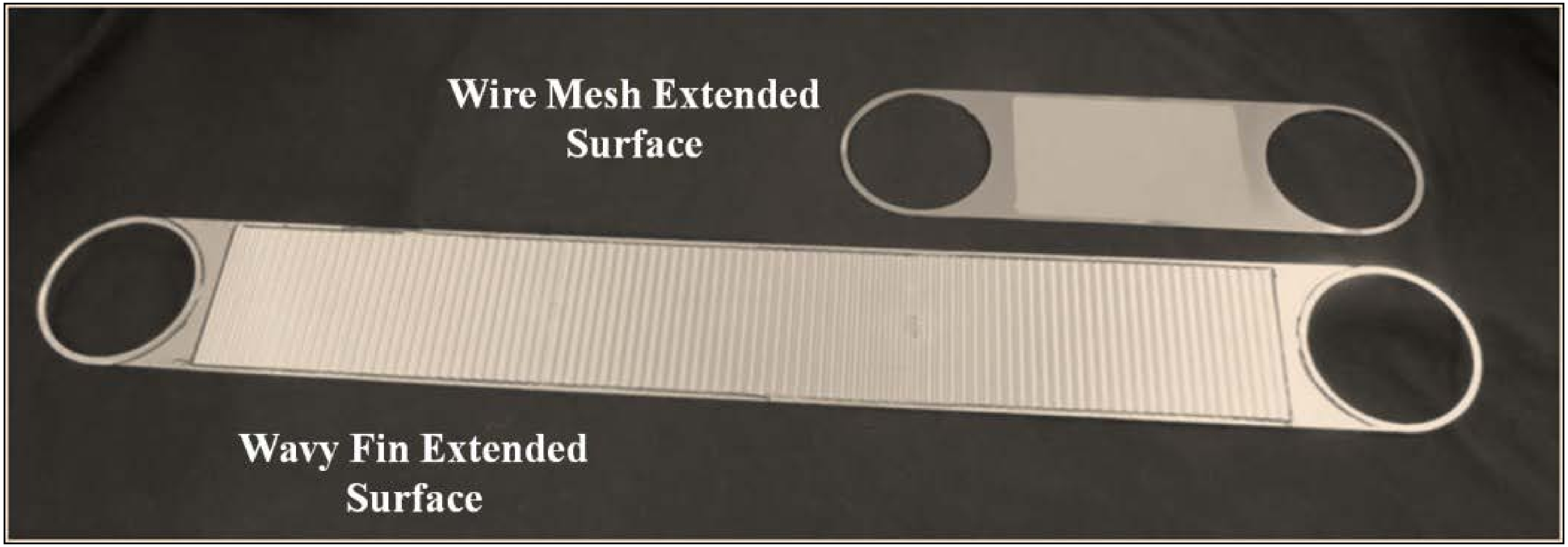


Plate-Matrix Heat Exchangers

Plate-Matrix Heat Exchanger Cores

- Multiple unit-cells are attached to each other at the high-pressure manifolds

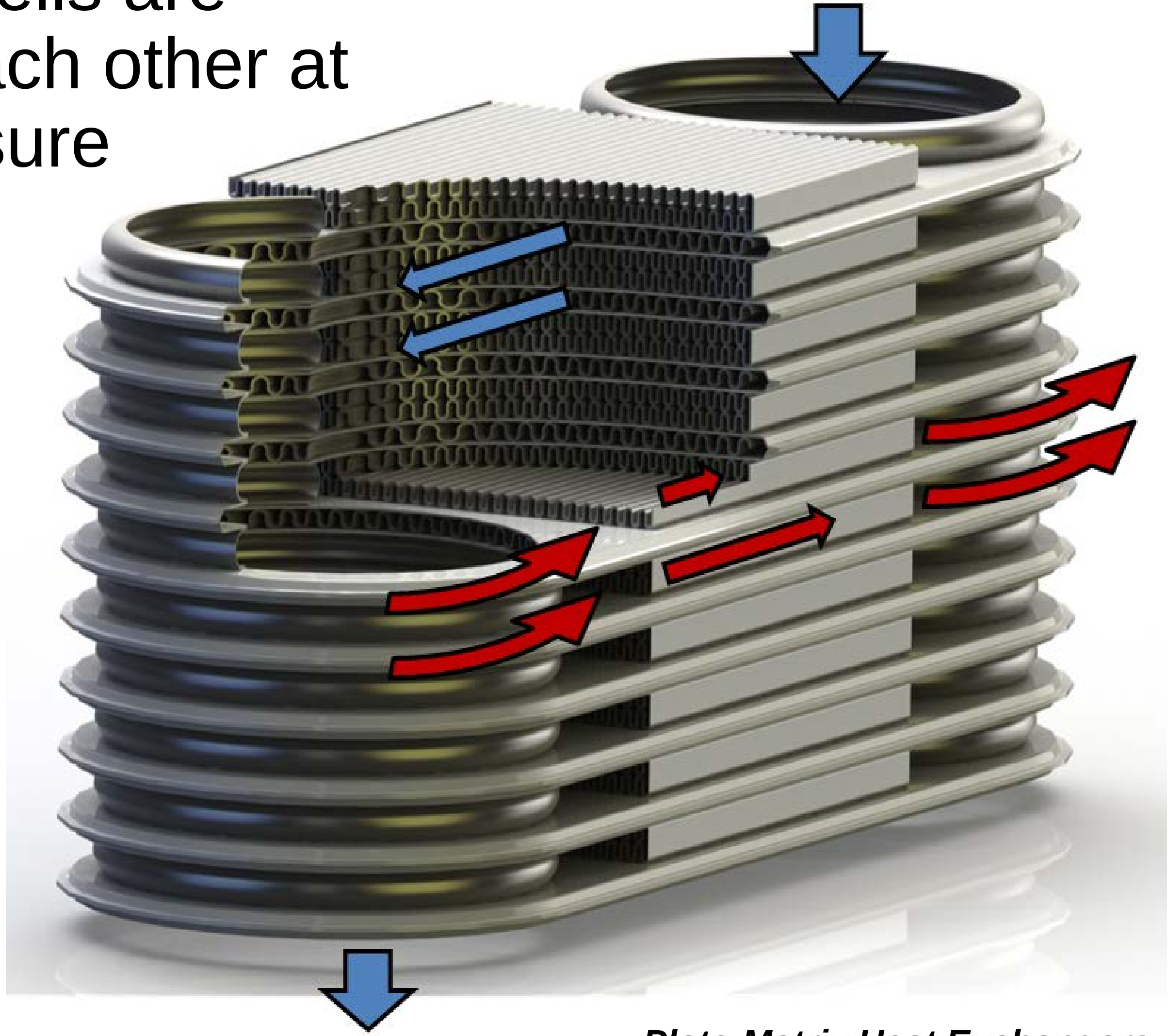
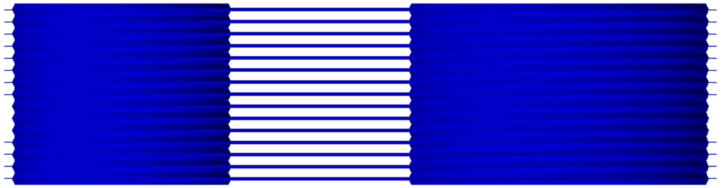


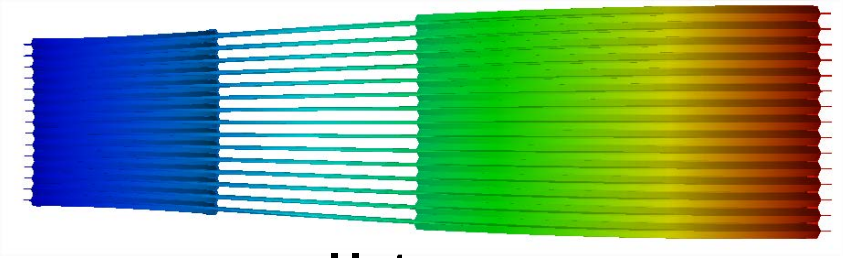
Plate-Matrix Heat Exchangers

Thermo-Mechanical Strain Tolerance

- Non-monolithic construction provides thermo-mechanical strain tolerance
  - Each unit cell represents a unique slip plane within the assembly
  - The associated low mechanical stiffness can accommodate temperature differences without inducing stresses on the assembly



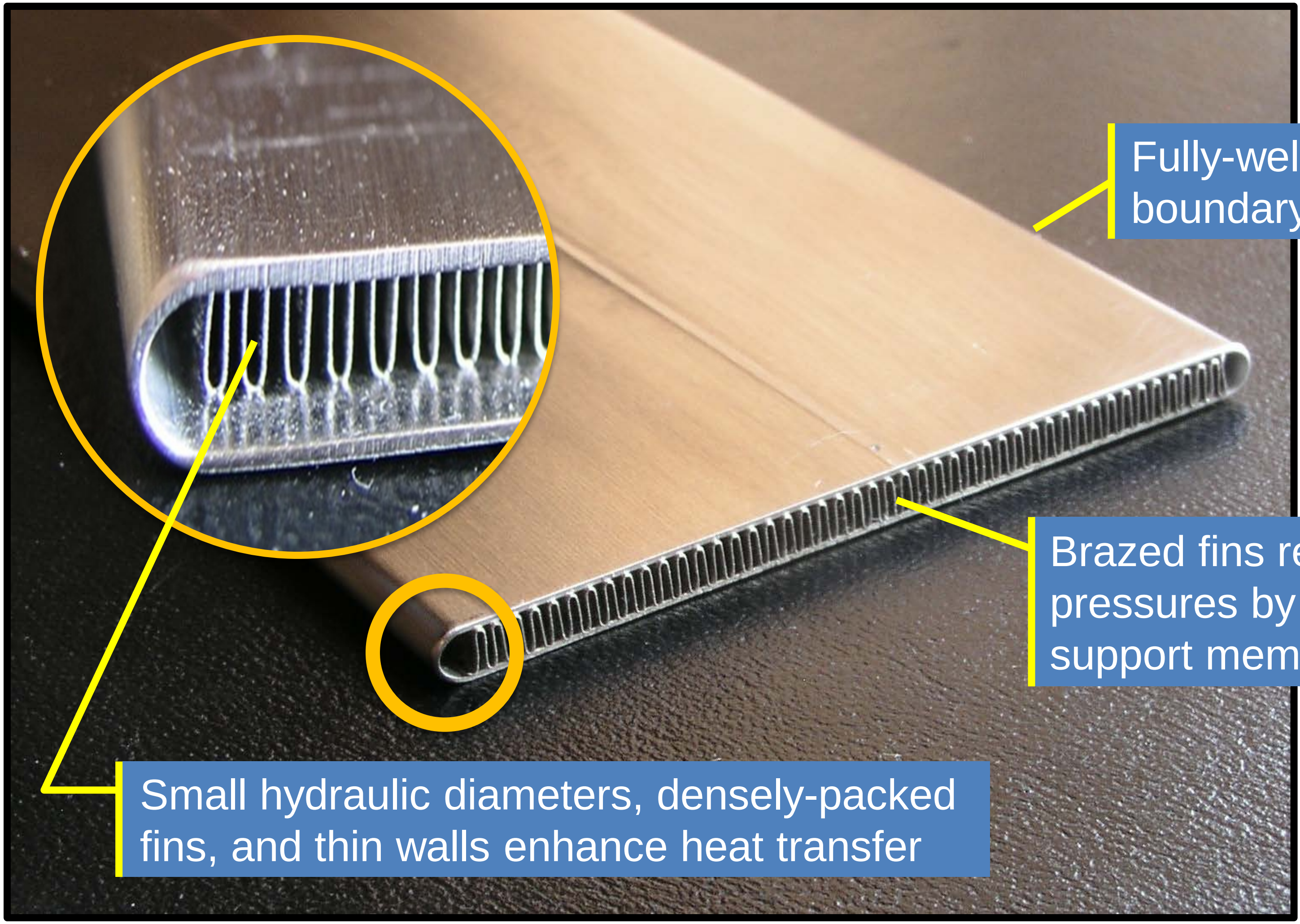
Cold (Isothermal)



Hot

Plate-Matrix Heat Exchangers

New Panel Cell Design



Fully-welded pressure boundary ensures sealing

Individually tested for quality

Brazed fins react high internal pressures by acting as tensile support members

Small hydraulic diameters, densely-packed fins, and thin walls enhance heat transfer

Customizable fin geometry

Heat Exchanger Mechanical Design and Validation for S-CO_2 Environments

James Nash

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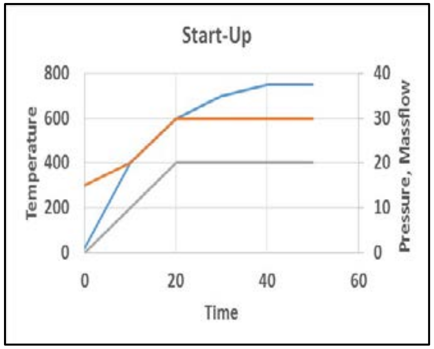
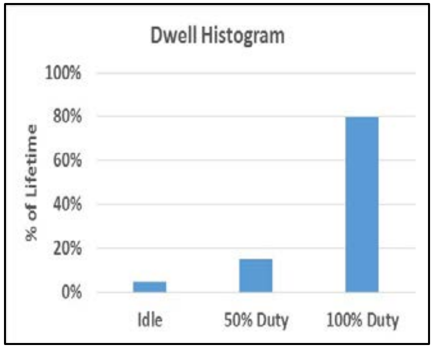
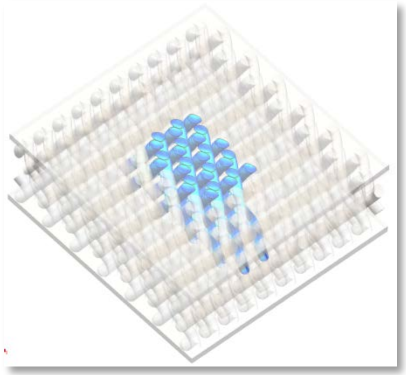
Design Methodology

Mission Definition



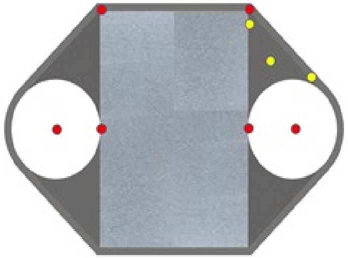


Mechanical Design and Simulations



Configured and Processed Materials Characterization

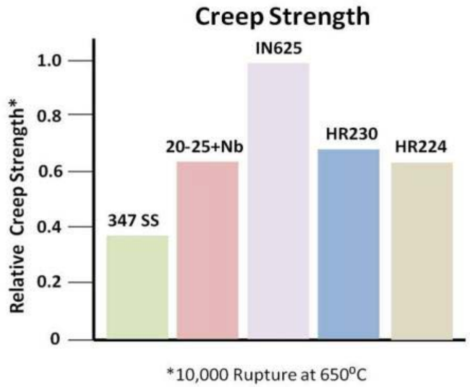
Thermal and Strain Validation & Endurance

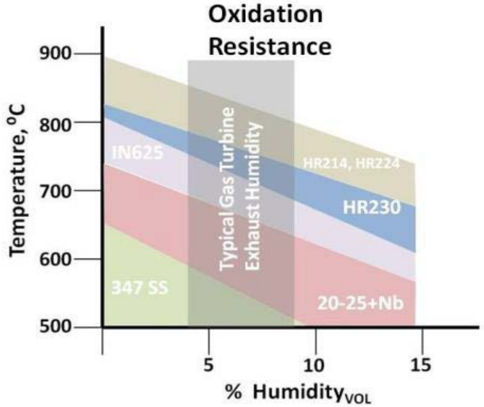


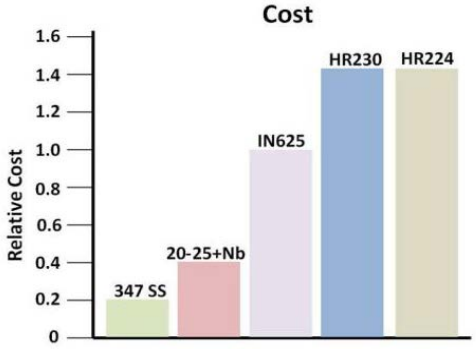
Requirements-to-Design Validation Method

- Specify Requirements in terms of mission profiles
  - Including dwells and transient maneuvers
- Render thermal hydraulic design into mechanical design
- Initial analyses with substrate material properties:
  - temperature
  - stress/strain
  - durability

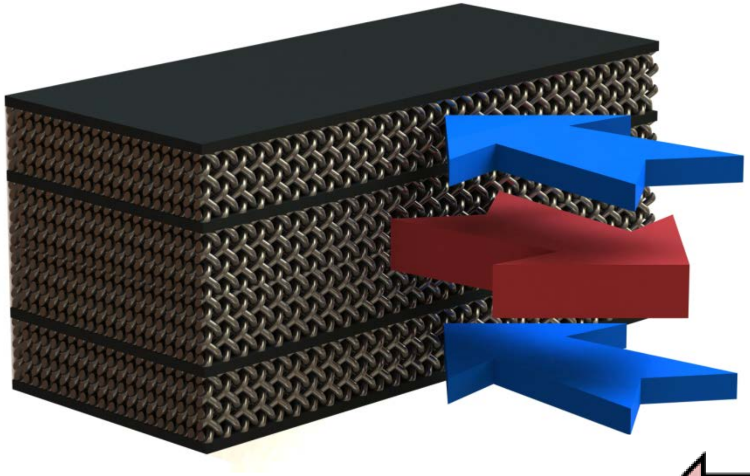
- Characterize as configured/processed materials as loaded in operation
  - creep
  - fatigue
- Validate/calibrate temperature and strain with actual heat exchanger cells
- Validate design with accelerated endurance testing
  - greater ΔT
  - greater pressure
  - design temperatures at control points.





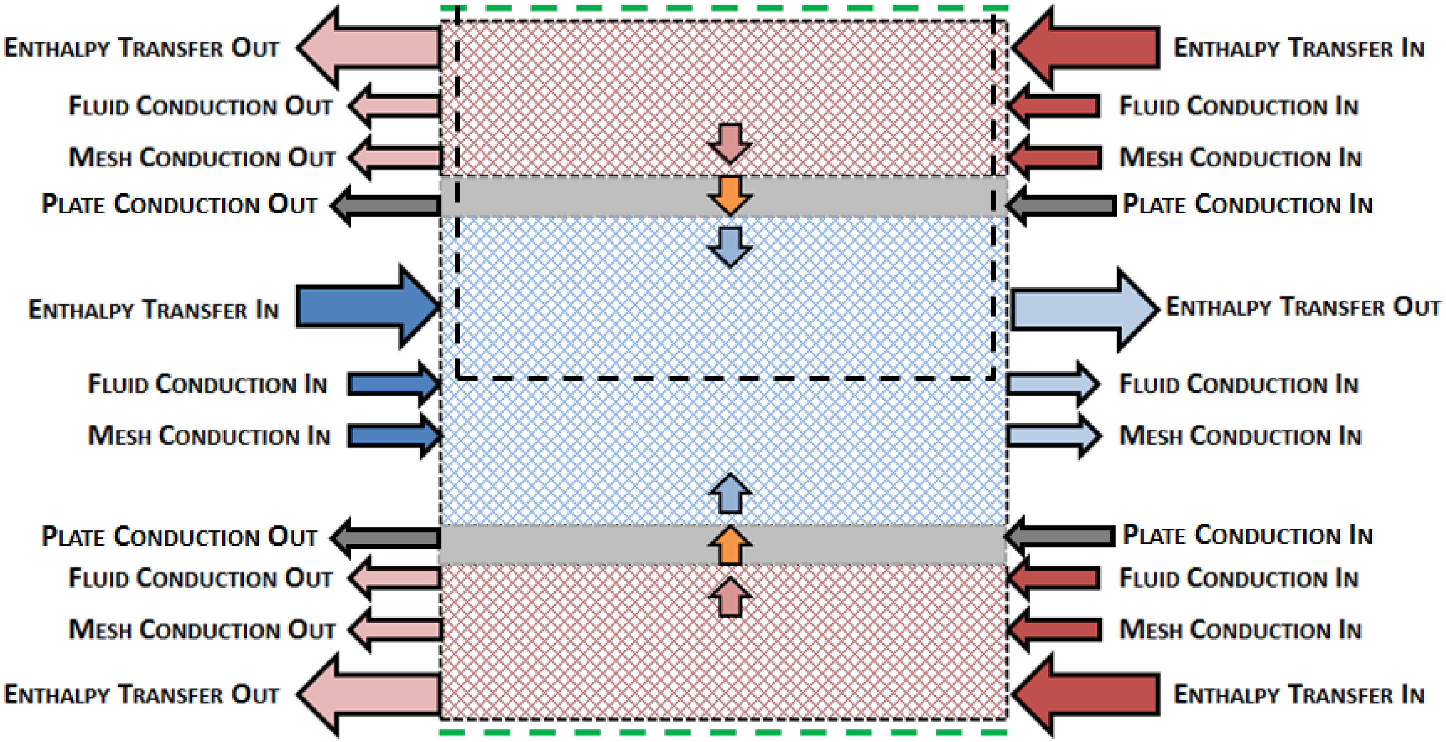


Heat Transfer Modeling



- Finite Difference modeling captures the non-intuitive nonlinear physical properties of supercritical fluids within heat exchangers (particularly in vicinity of critical point)
- Enthalpy change is used to calculate the heat gain (or loss) so as to capture the significant pressure dependence of the internal energy of the fluid
  - Δh(T,P) used instead of $\dot{m}c_p$(T)

- Axial conduction losses – which may be significant in high-ε designs – are captured for both the parent material and the heat transfer enhancing structures

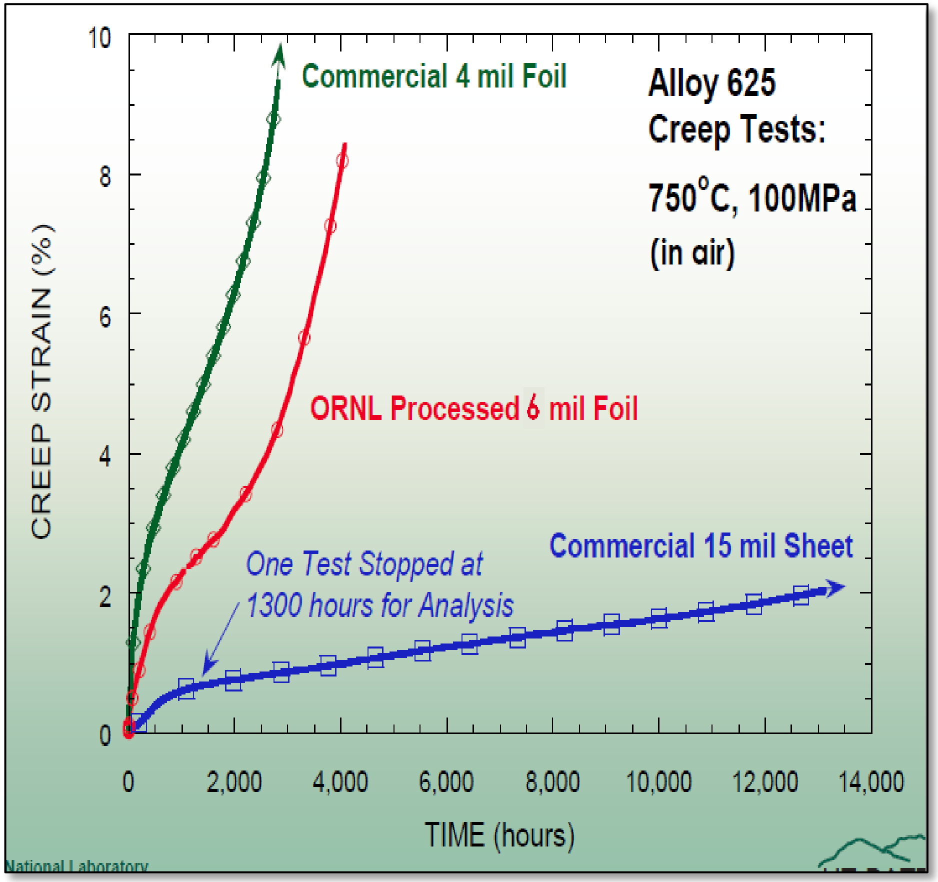


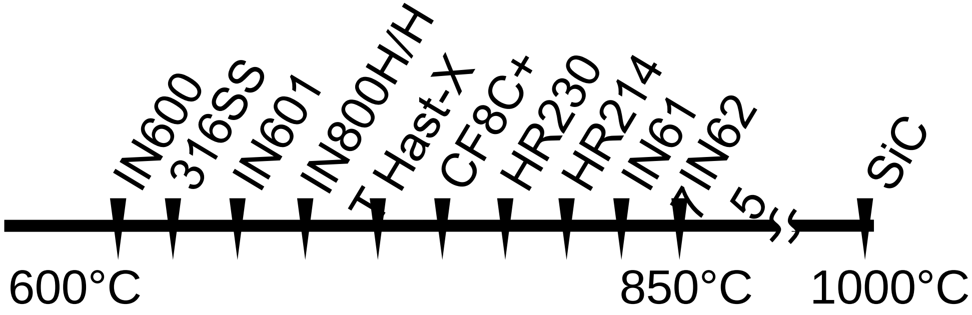
Enthalpy Transfer Out
Fluid Conduction Out
Mesh Conduction Out
Plate Conduction Out
Enthalpy Transfer In
Fluid Conduction In
Mesh Conduction In
Plate Conduction Out
Fluid Conduction Out
Mesh Conduction Out
Enthalpy Transfer Out

Enthalpy Transfer In
Fluid Conduction In
Mesh Conduction In
Plate Conduction In
Enthalpy Transfer Out
Fluid Conduction In
Mesh Conduction In
Plate Conduction In
Fluid Conduction In
Mesh Conduction In
Enthalpy Transfer In

Creep Considerations

- High solidity structures – thick-walled tubes, dense extended surfaces.
- Ni-Cr alloys with precipitates in grain boundaries
- Choices: Alloy 625, Alloy 617, Alloy 718, Alloy 230, HR214™, HR224™
- Be careful of thickness. Sheet properties may not represent foil. (Grain size vs. thickness?)

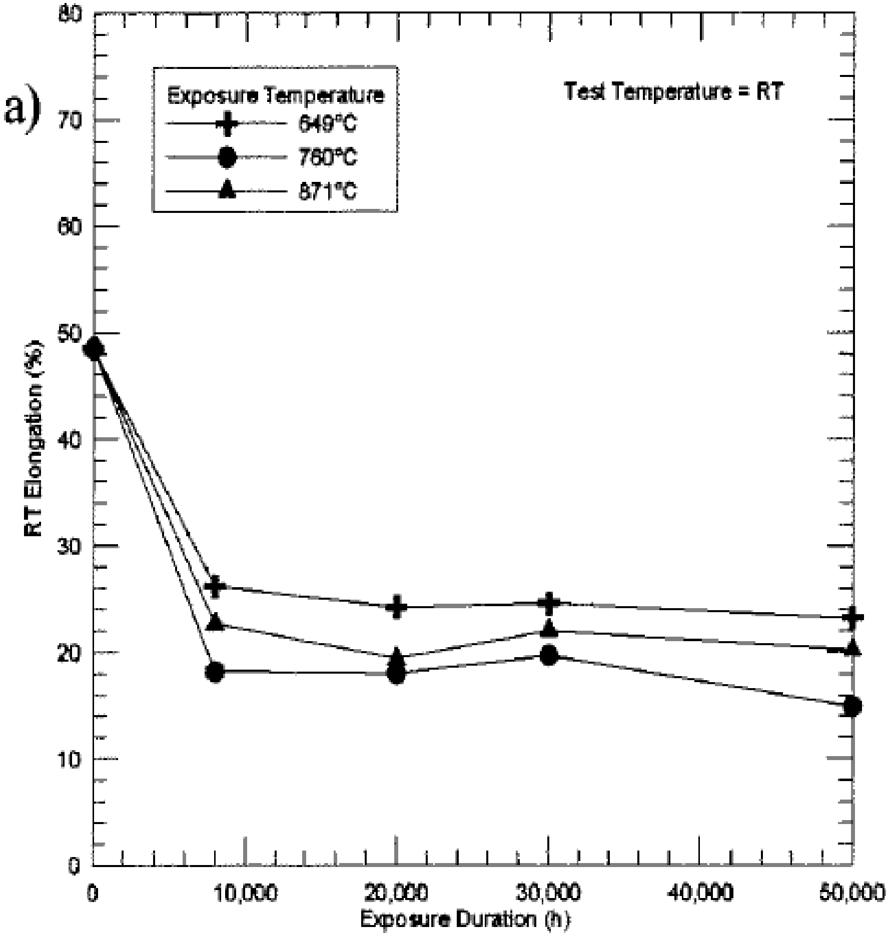




For 10,000 hour creep life at 70 MPa

Fatigue Considerations

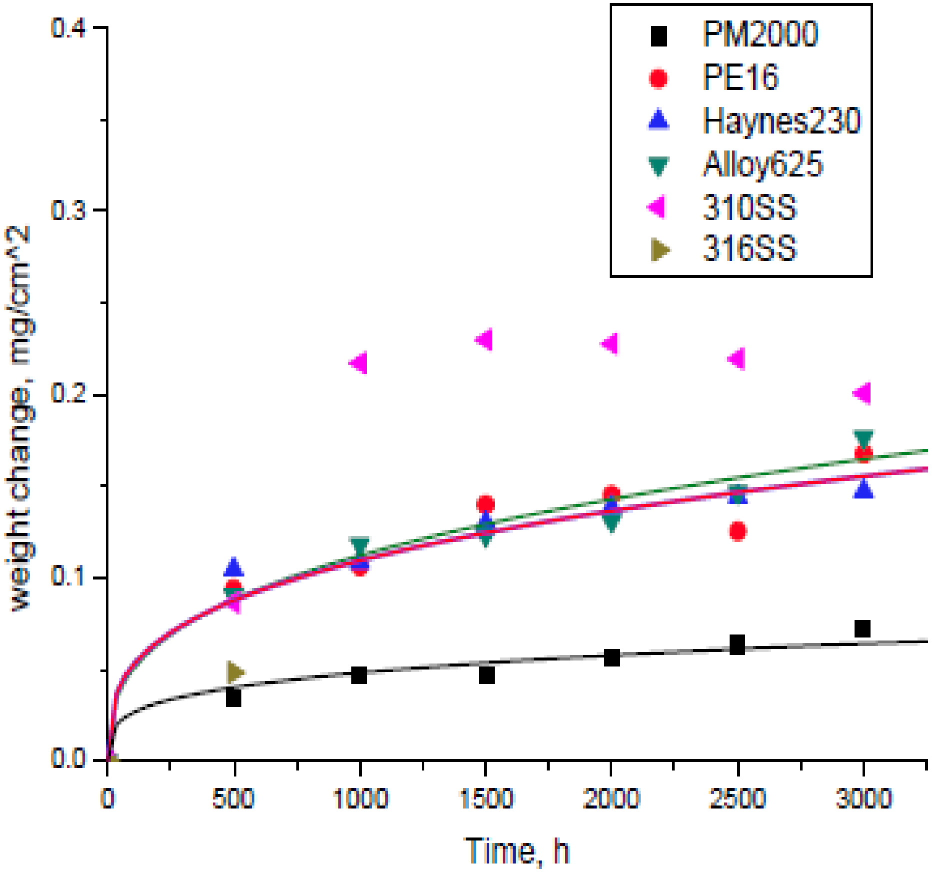
- Highly design dependent gradient selection for ΔT
- Structural compliance
  - Bigger is NOT stronger!
- Thick-thin avoidance
- Stress in weld-heat affected zones.
- Ductility – as processed, after aging



HR120 elongation with exposure at 649, 760 and 871ºC. Source: Pike & Srivastava Haynes Int’l

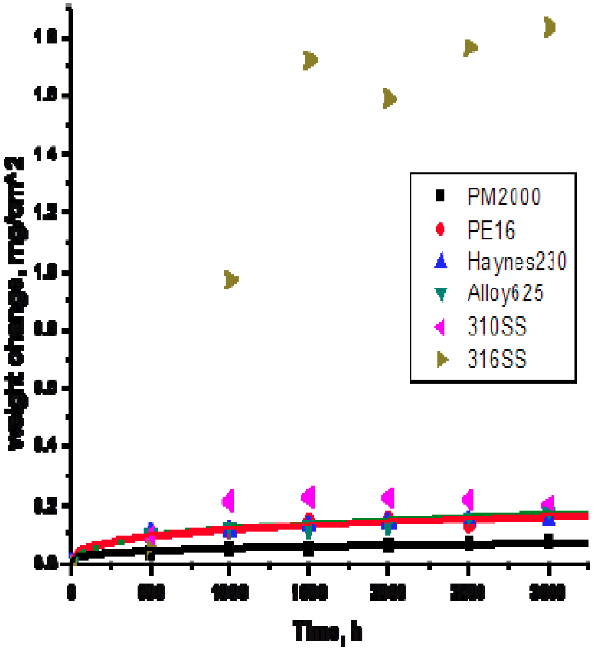
Corrosion Considerations

- Oxidation
- Scale evaporation with high temperature and/or humidity addition
- Ni and Cr basic protection
- Rare-earth additions to stabilize scale
- Aluminum addition for very low volatile Al_2O_3 scale over chromia
- >20% Cr is key to oxidation resistance at 650^{0}C according to Sridharan et al.

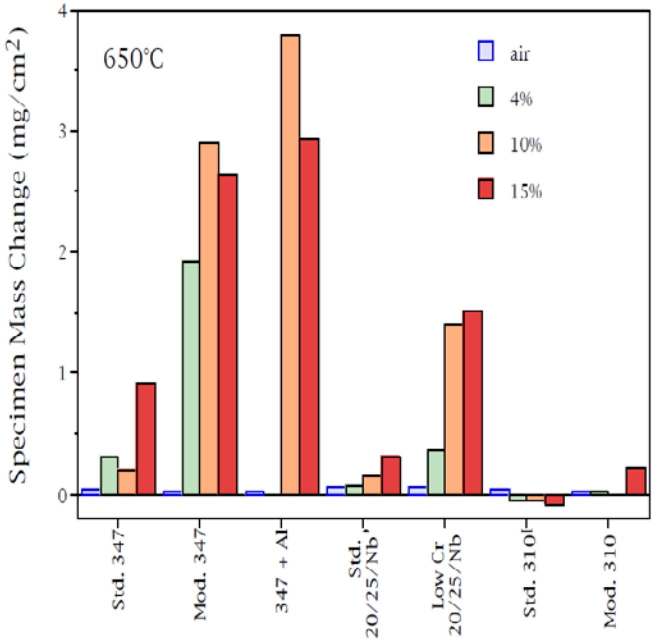


Source: Sridharan, Anderson, et al - University of Wisconsin, sCO_2 Power Cycle Symposium, Boulder, CO 2011

Type 310SS 650°C Oxidation sCO_2 vs. Air



Sridharan, Anderson, University of Wisconsin, et al, sCO_2 Power Cycle Symposium, Boulder, CO 2011

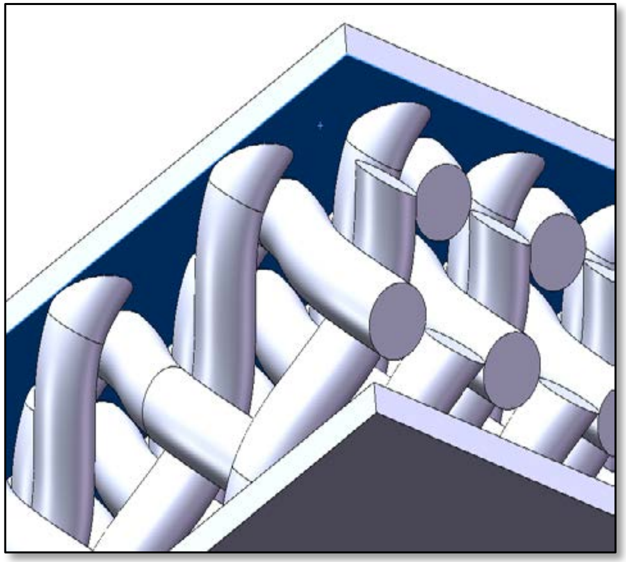


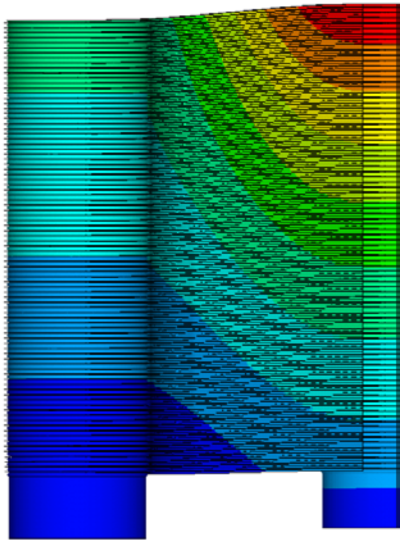
Pint (ORNL) and Rakowski (Allegheny Ludlum), Effect of Water Vapor on the Oxidation Resistance of Stainless Steel

1. 0.25 mg/cm^2 gain in sCO_2 vs. 0.045 in laboratory air after 1,000 hours
2. Aluminum addition with addition of humidity?

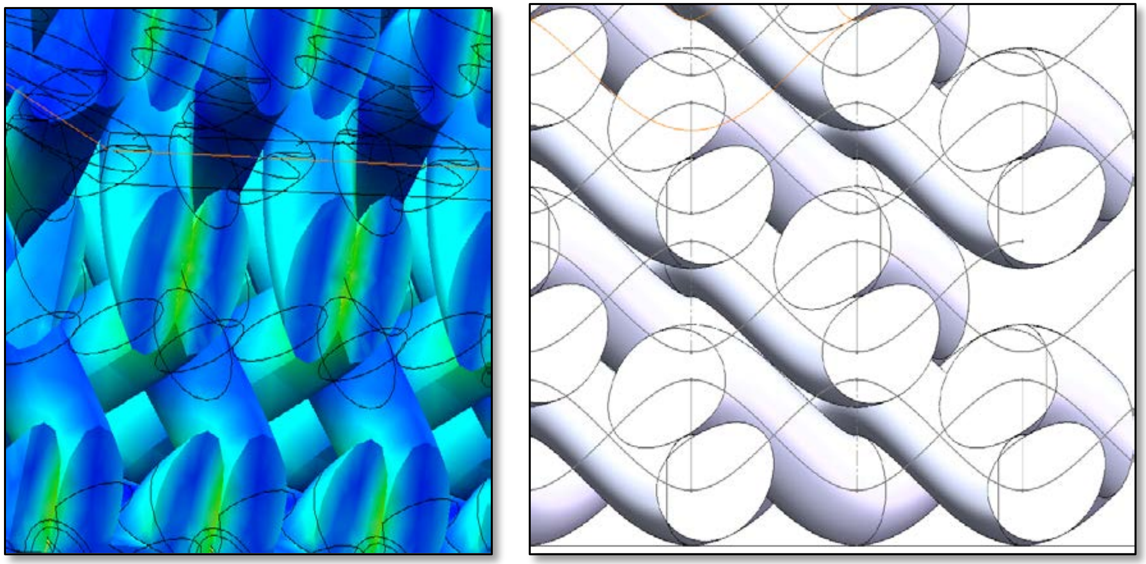
Simulations

- Conduct thermal and structural FEA to determine temperature, stress, and strain
- Identify ‘control points; - details where damage may accumulate
- Perform initial life analyses to quantify creep, and fatigue



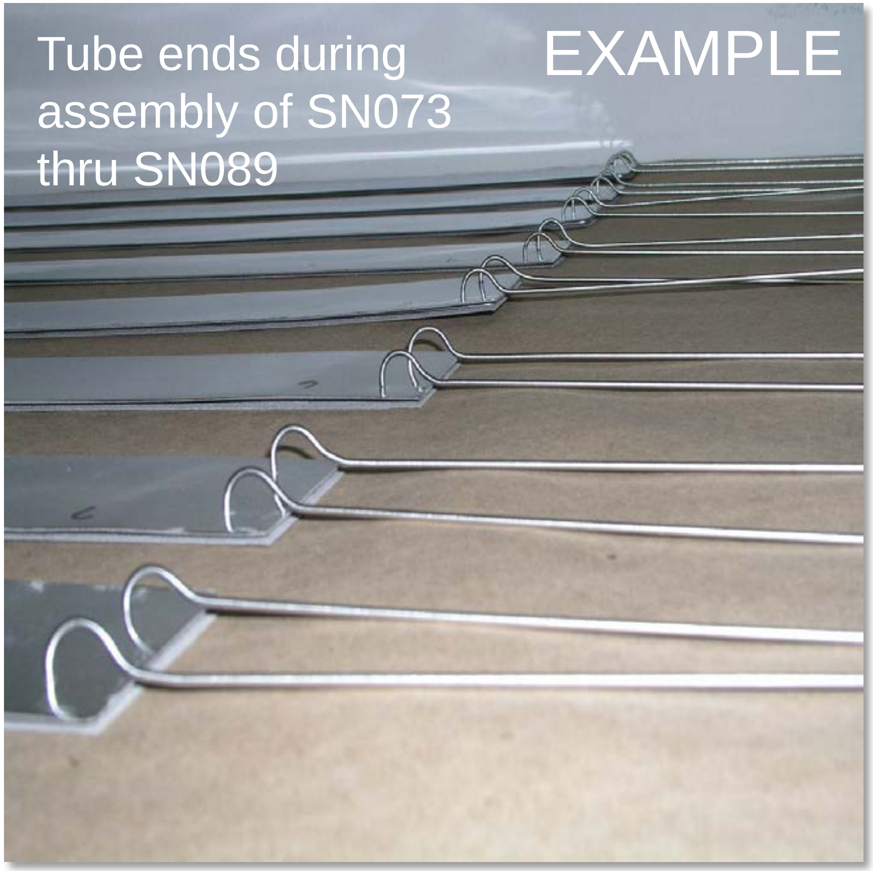


Core strain analysis



Wire-mesh analysis for creep and pressure-fatigue simulation.

Testing As Configured/Processed Material



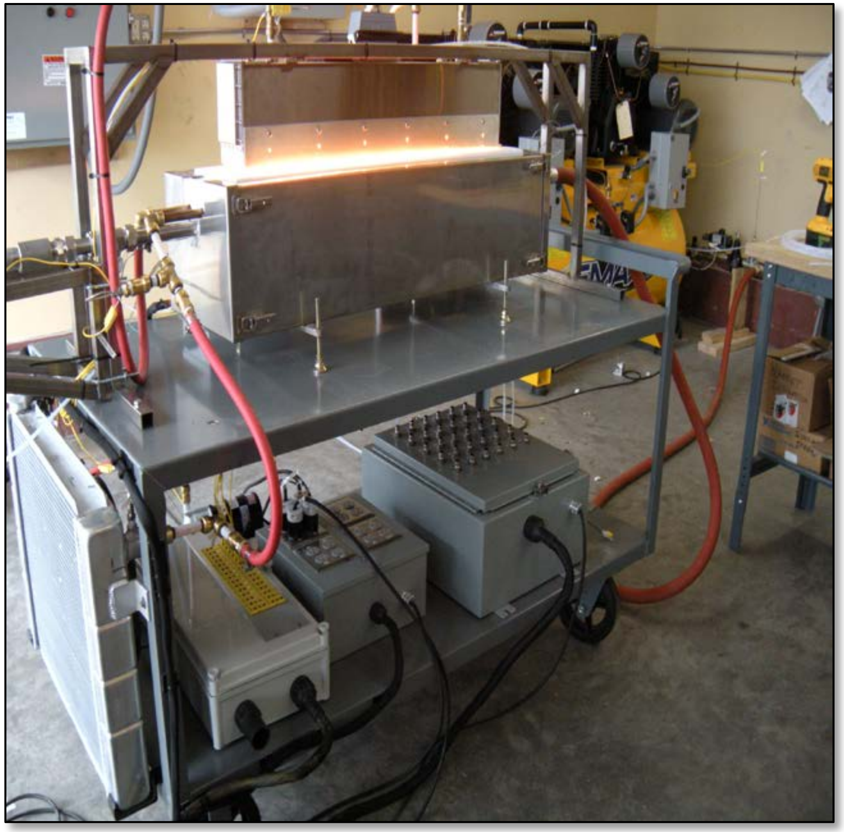
This final batch of heat exchanger cells were of high quality, leak tight and suitable for creep tests

- Example: If pressure is the steady load dominating creep or fatigue, pressure is used in characterization
  - Includes all configuration and processing effects
  - Avoids interpretation of ‘like’ data and loading.

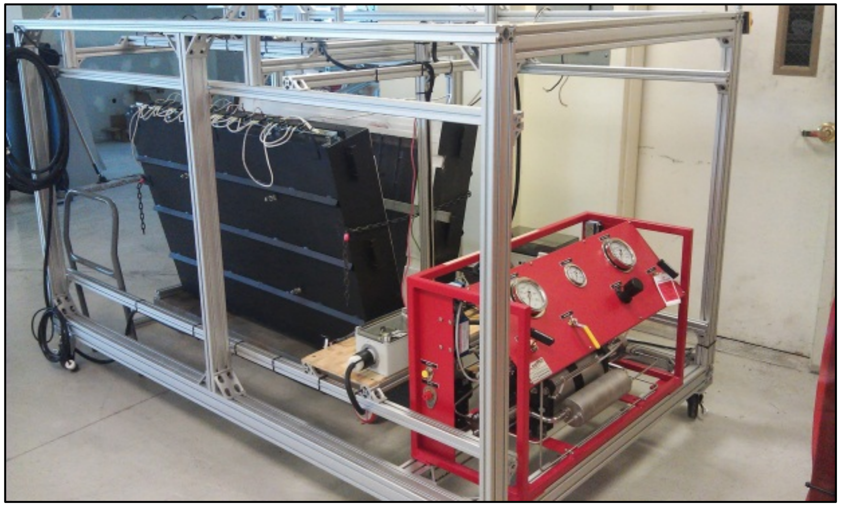
- sCO_2 pressurization for possible corrosion interaction

Thermo-Mechanical Fatigue Testing

- If high radiant flux loads produce damage, material is characterized accordingly
- Burner rig or furnace is appropriate for characterization under cyclic convective loading



Radiant (High Flux) Test Rig



High Temperature Furnace

Hydraulic Design with Supercritical Fluids

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Hydraulic Design – Supercritical Fluids

$$\Delta P_{total} = \Delta P_{inlet\,manifold} + \Delta P_{entrance} + \Delta P_{internal\,flow} + \Delta P_{exit} + \Delta P_{outlet\,manifold}$$

$$\Delta P_{internal\,flow} = f\,\frac{L}{D_h}\,\frac{1}{2}\,\rho\,V^2$$

$$f = f\,(e, D_h, V, \rho, \mu)$$

$$V = \frac{\dot{m}}{\rho\,A_f}$$

Geometric parameters

Fluid properties and mass flow

Hydraulic Design – Modeling Considerations

- The non-linear behavior of supercritical fluids – particularly near the critical point – makes endpoint calculations risky
  - Finite difference or integrated methods necessary to capture non-intuitive property behavior

- The strong property dependence on pressure makes sensible heat calculations risky
  - Use enthalpy change Δh(T,P) to calculate energy gain or loss, instead of $\dot{m}c_p$

Hydraulic Design – Correlations and Calculations

- Internal Flow $\Delta P = f \frac{L}{D_h} \frac{1}{2} \rho V^2$
  - *f* may be derived from:
    - Moody Chart
    - Kays and London (NB: friction factor *f* = 4*Fanning Friction Factor)
    - empirical correlation

- Porous Media $\Delta P = \frac{Q\mu L}{kA_f}$

Q = volumetric flow rate
κ = permeability

- Wire-Mesh $f = \frac{2\rho\Delta P}{G^2\beta t}\left(\frac{1-\varepsilon}{\varepsilon}\right)^{0.4}$

G = internal mass velocity
β = surface area/volume
ε = porosity

- CFD

Hydraulic Design – Flow Distribution

Un-guided Counterflow Headers:

- Rising static pressure along inlet header with deceleration - uniform
- Declining static pressure in discharge header, but exacerbated by non-uniform profile approaching exit plane
- Uniform flow created by proper area ratio accounting for differences in density and velocity profile

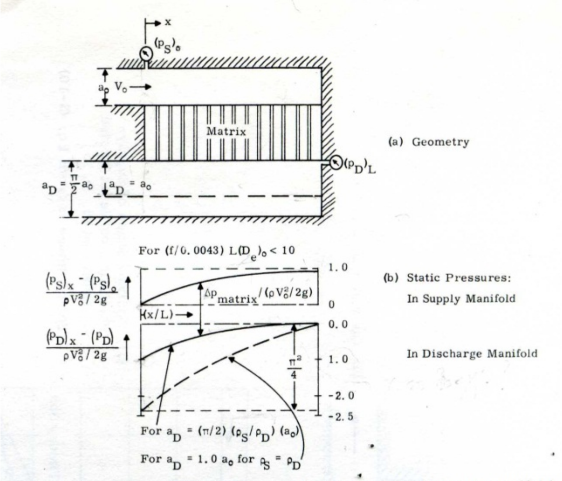
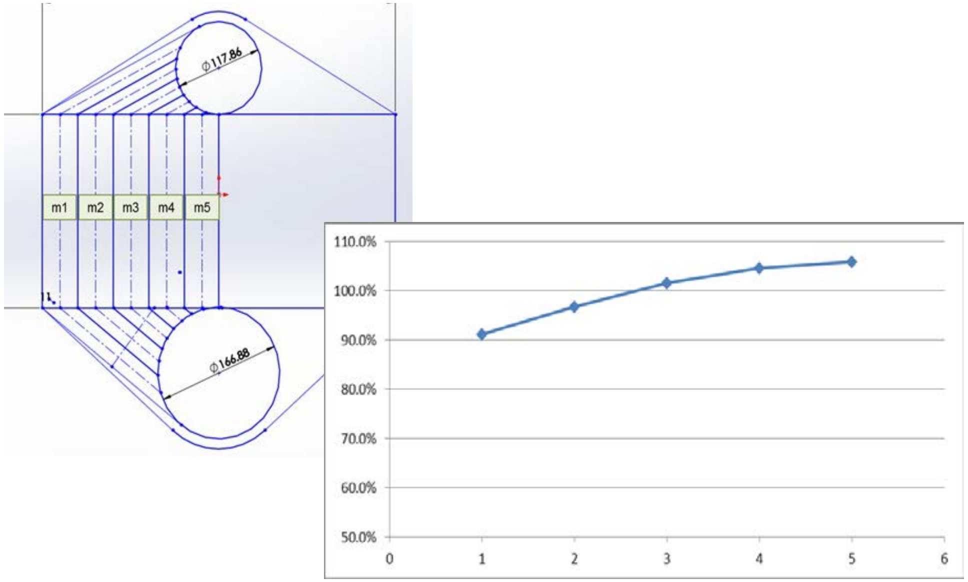


Fig. 3-5. Counterflow Arrangement of Box-Shaped Supply Manifold with Box-Shaped Discharge Manifold



Guided Headers:

- Unequal lengths imply unequal resistances
- Net pressure loss is same irrespective of path
- Flux adjusted to achieve equal pressure losses for each path
- Heat transfer performance assessed on a mass-averaged basis

Questions?

Thank You

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