SAND2015-9473C

Exceptional service in the national interest

Sandia National Laboratories

Heat Exchangers & Additive Manufacturing

EWI Additive Manufacturing Consortium (AMC) Fall Meeting

October 29, 2015, Santa Fe, New Mexico

Carlson, M., Keicher, D.

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

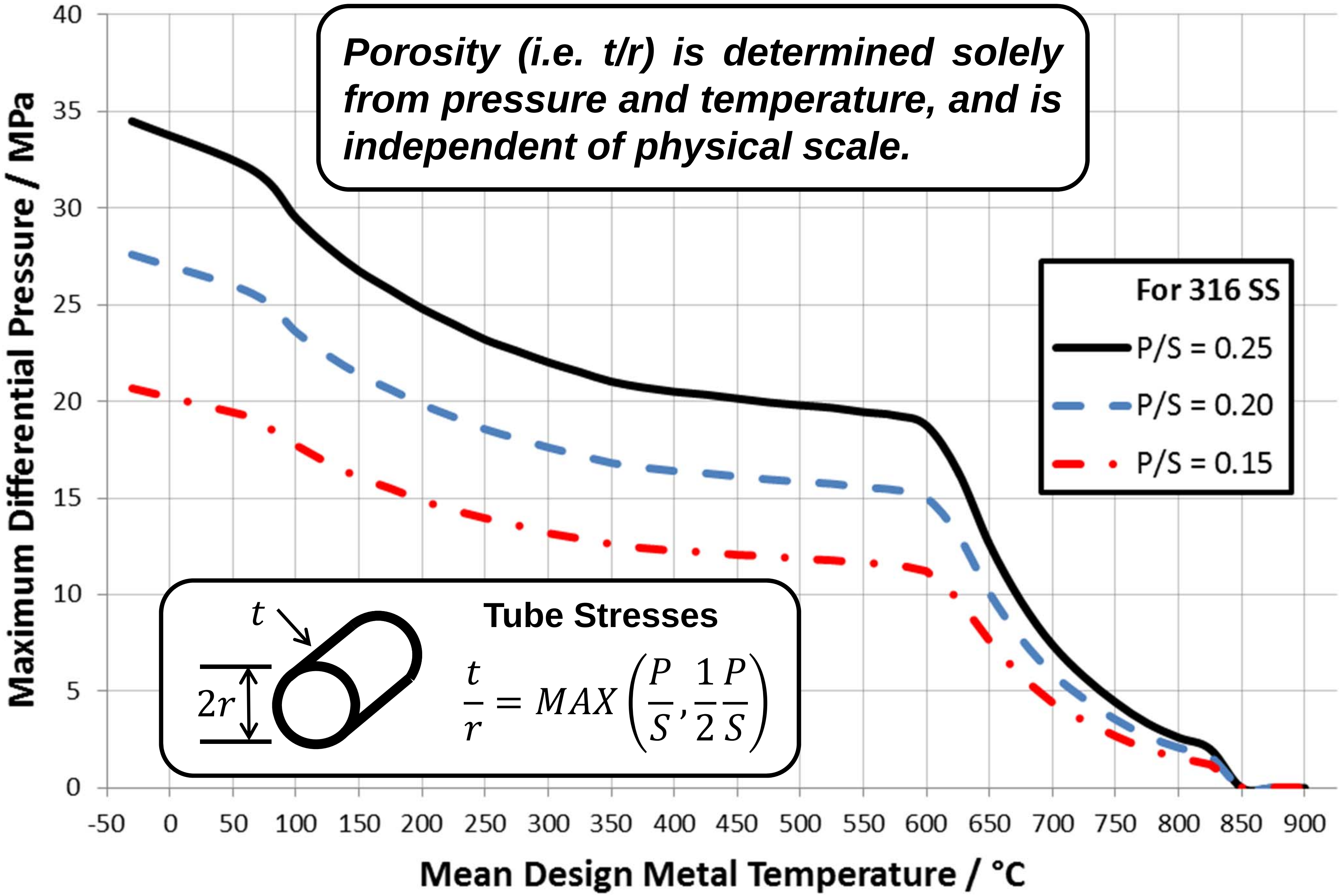
Overview – Advanced HXers

- **The Opportunity for AM with Heat Exchangers**
  - Small channels allow for compact, lower-cost devices
  - Optimum thermal hydraulics require complex, varied surfaces
  - Commercial applications require enormous surface areas
- **Notable AM Heat Exchanger Projects**
  - The Autodesk Within – 3T-RPD prototype
  - Fabrisonic microchannel heat sinks
  - Prototyped devices from Thar, Infinity Turbines
- **AM Heat Exchanger Development at Sandia**
  - AM ceramic casting cores for cast metal heat exchangers
  - Pre-stressed ceramic heat exchangers for high temperatures
  - Advanced 3-dimensionally curved channels for enhancement

Heat Exchangers & Additive Manufacturing

THE OPPORTUNITY FOR ADDITIVE

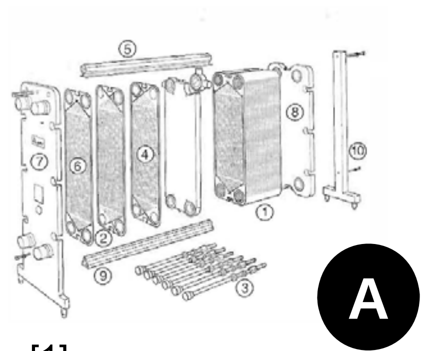
Heat Exchanger Porosity



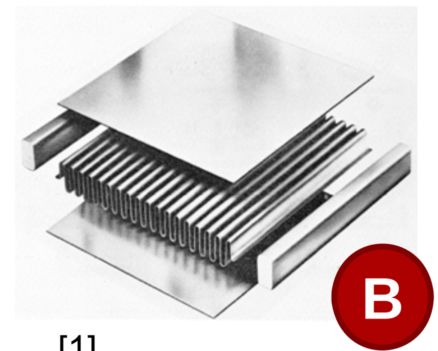
Small Flow Channel Compactness

$$\underbrace{\beta}_{Compactness} = \frac{\overbrace{A_s}^{Surface\ Area}}{\underbrace{V}_{Volume}} = 4\frac{\overbrace{\phi}^{Porosity}}{\underbrace{d_h}_{Channel\ Size}}$$

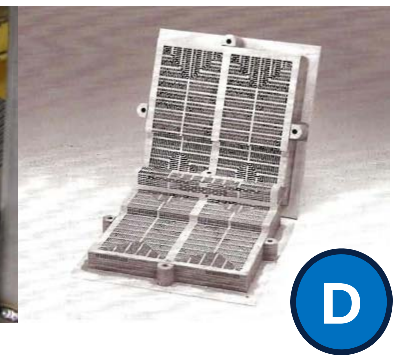
Surface area per unit volume scales inversely with channel size, and with porosity (temperature and pressure).



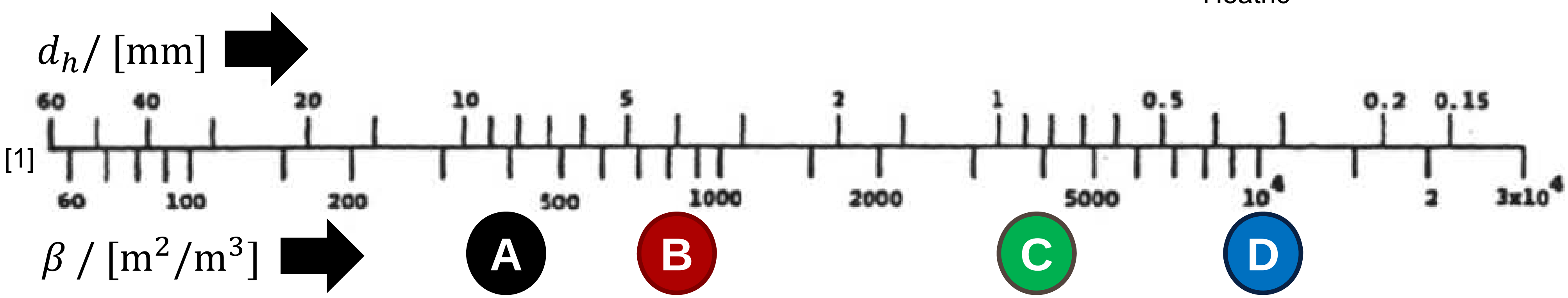
[1]



[1]

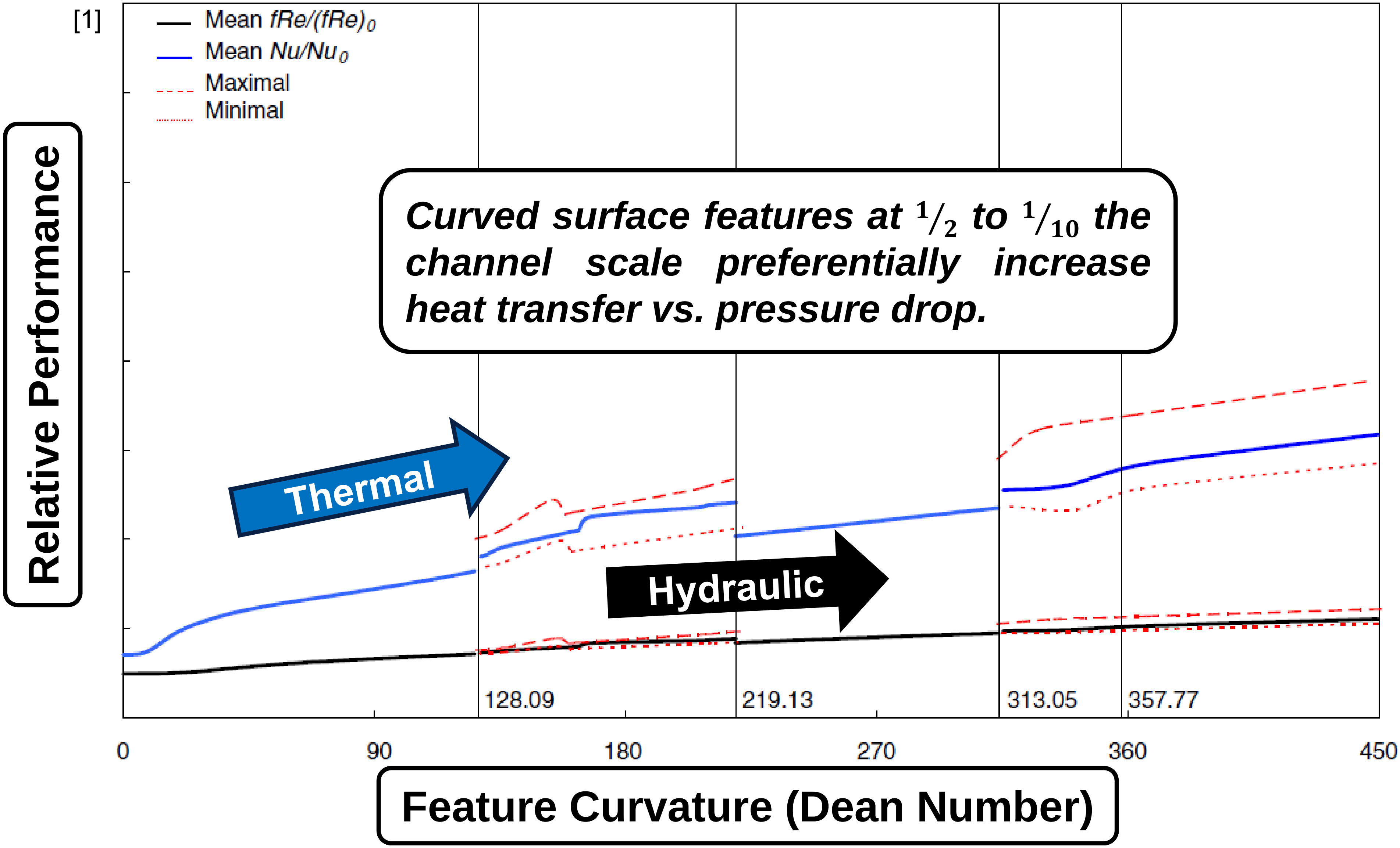


Heatric



[1] J. E. Hesselgreaves, *Compact heat exchangers : selection, design and operation*. Amsterdam: Pergamon, 2001.

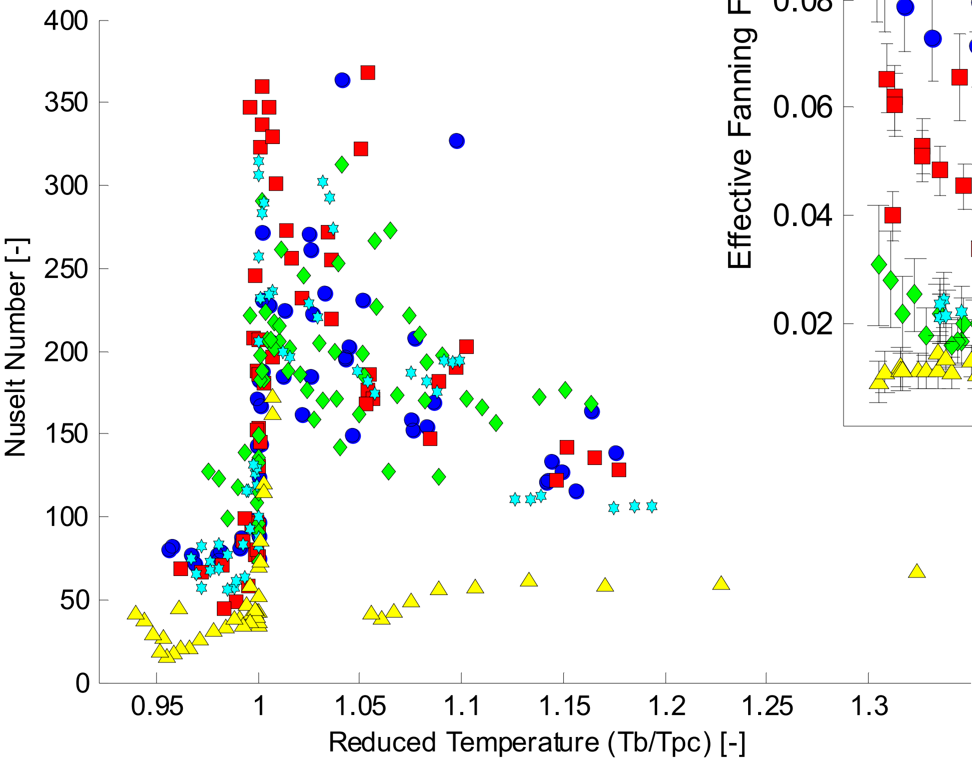
Optimizing Thermal Hydraulics

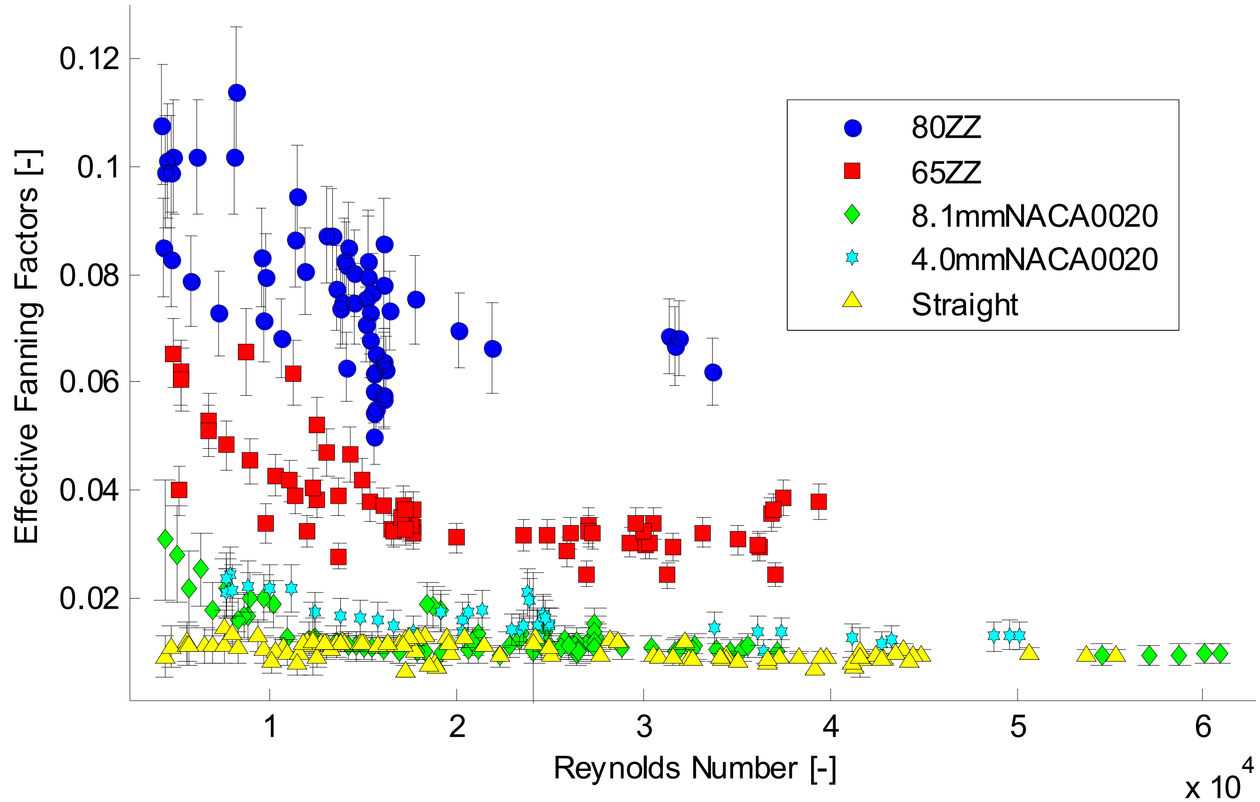


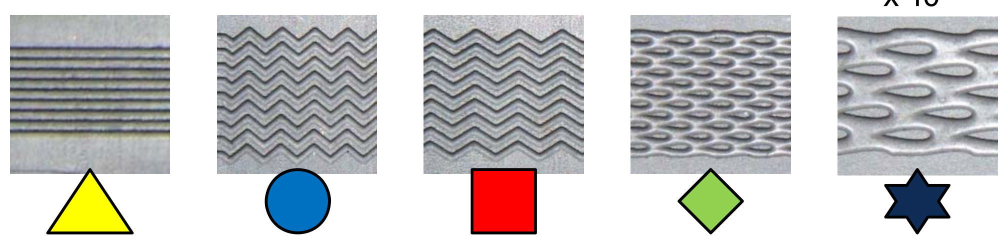
[1] L. Wang and F. Liu, "Forced convection in slightly curved microchannels," International Journal of Heat and Mass Transfer, vol. 50, no. 5–6, pp. 881–896, Mar. 2007.

Thermal Hydraulic Performance

Same Nusselt number, different friction factors.







Carlson, M. (2012). *Measurement and Analysis of the Thermal and Hydraulic Performance of Several Printed Circuit Heat Exchanger Channel Geometries* (Master of Science). University of Wisconsin - Madison, Madison, WI.

Overall Size of Commercial Units

Commercial units contain acres of active heat transfer surface area.

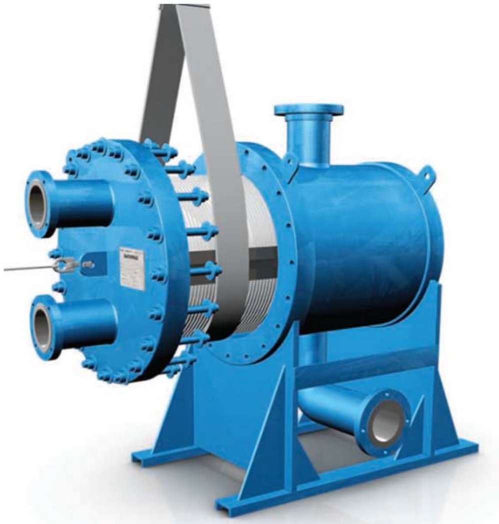
$$\beta = \frac{A_s}{V} = \frac{4\phi}{d_h}$$

Linde Gas Coil-Wound
β from 10 to 300 [m²/m³]

Graham Shell and Tube
β from 10 to 200 [m²/m³]

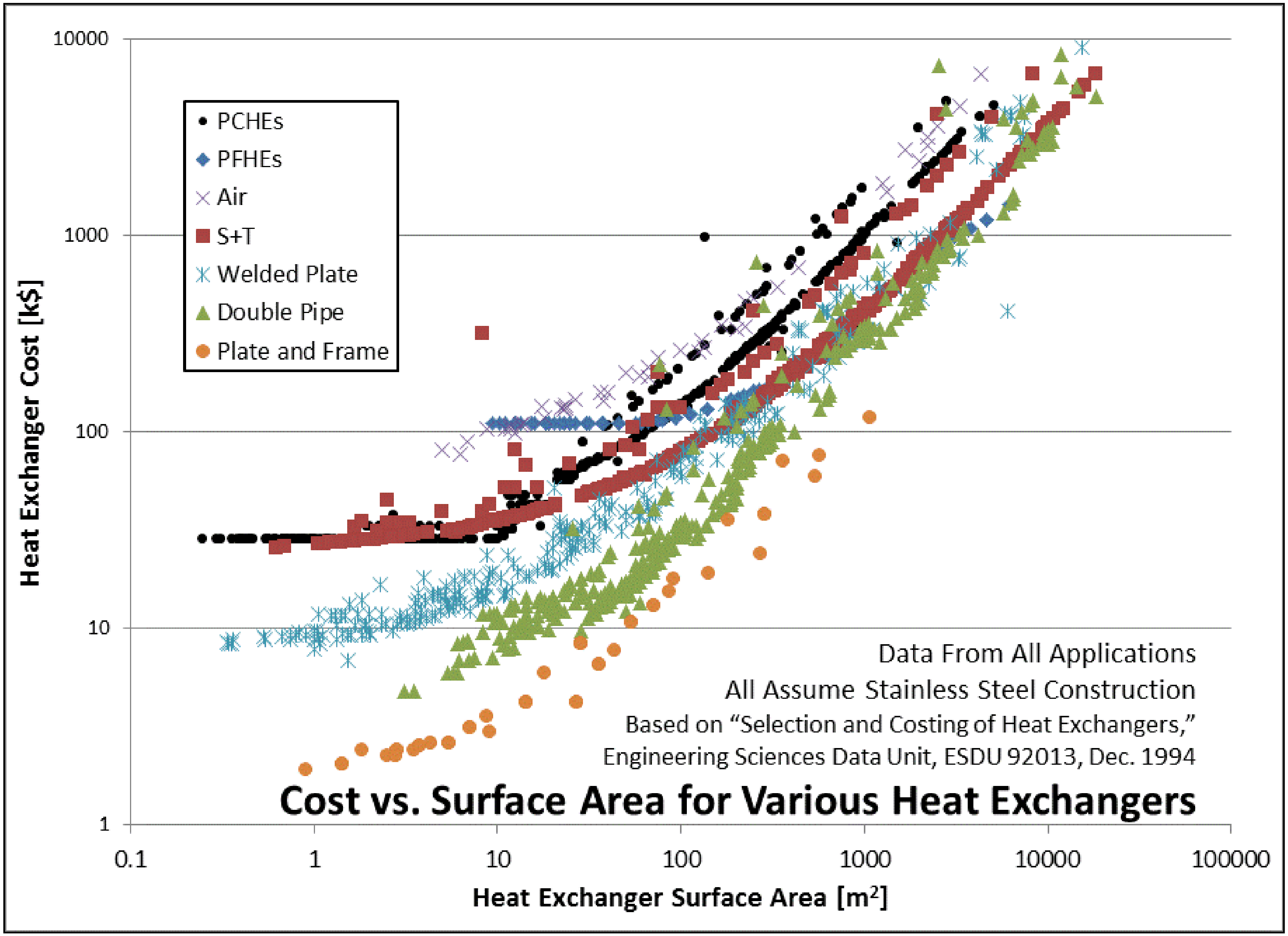
Chart Plate-Fin
β from 200 to 800 [m²/m³]

Heatric Printed Circuit
β from 200 to 5000 [m²/m³]



Tranter Shell and Plate
β from 100 to 600 [m²/m³]

Tight Competition on Cost vs. Area



Heat Exchangers & Additive Manufacturing

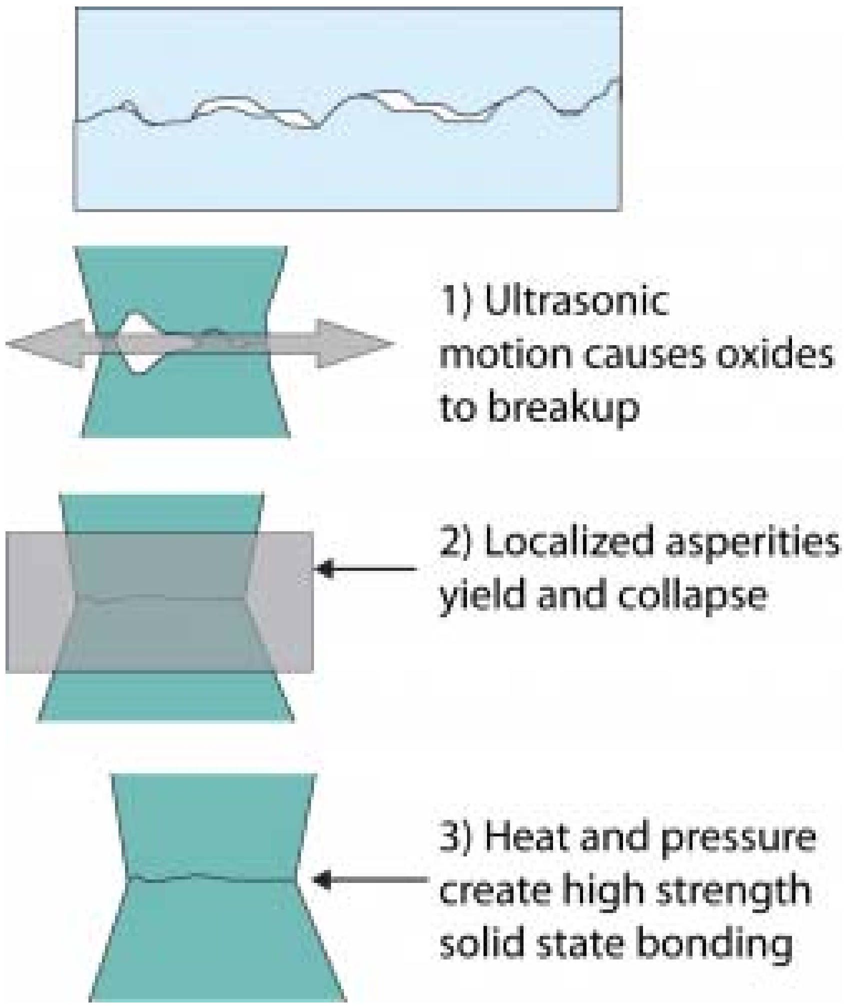
NOTABLE AM HEAT EXCHANGERS

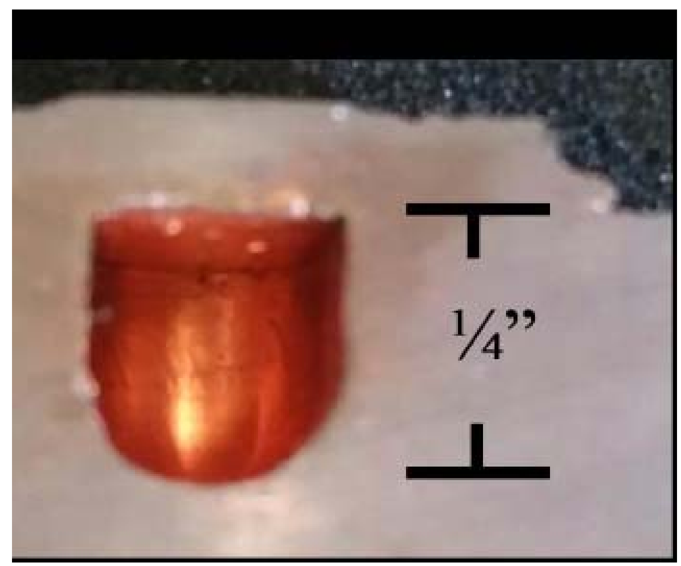
Within – 3T-RPD prototype

- Designed by Within technologies, now part of Autodesk
- Fabricated using an EOS DLMS system
- AlSi10Mg Aluminum
- Produced as a prototype for a Formula 1 high-performance oil cooler

Fabrisonic Ultrasonic AM

Sandia National Laboratories

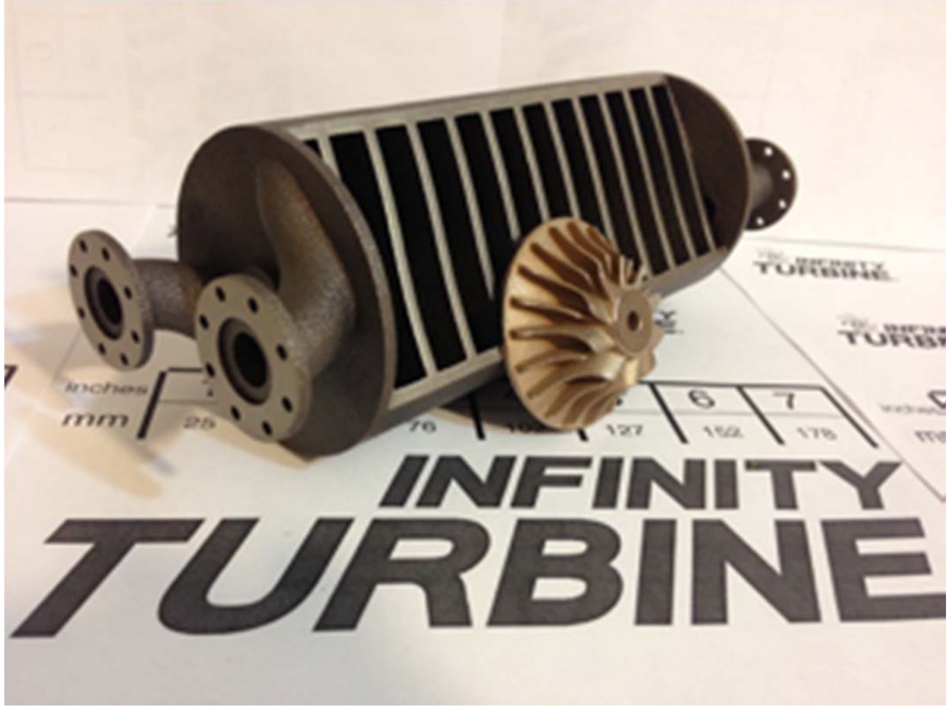




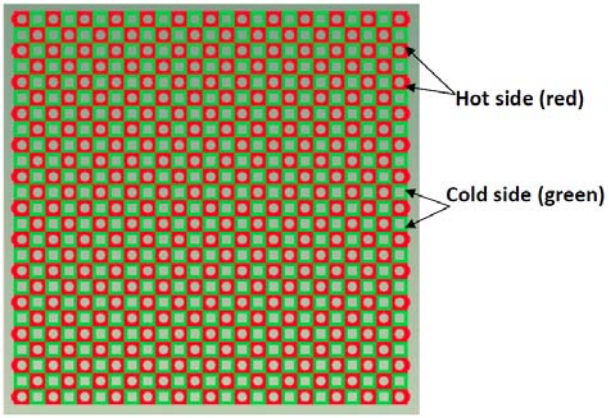
Other Prototyped Devices

Helical Plate Style

[1]



Checkerboard Plate Style



[2]

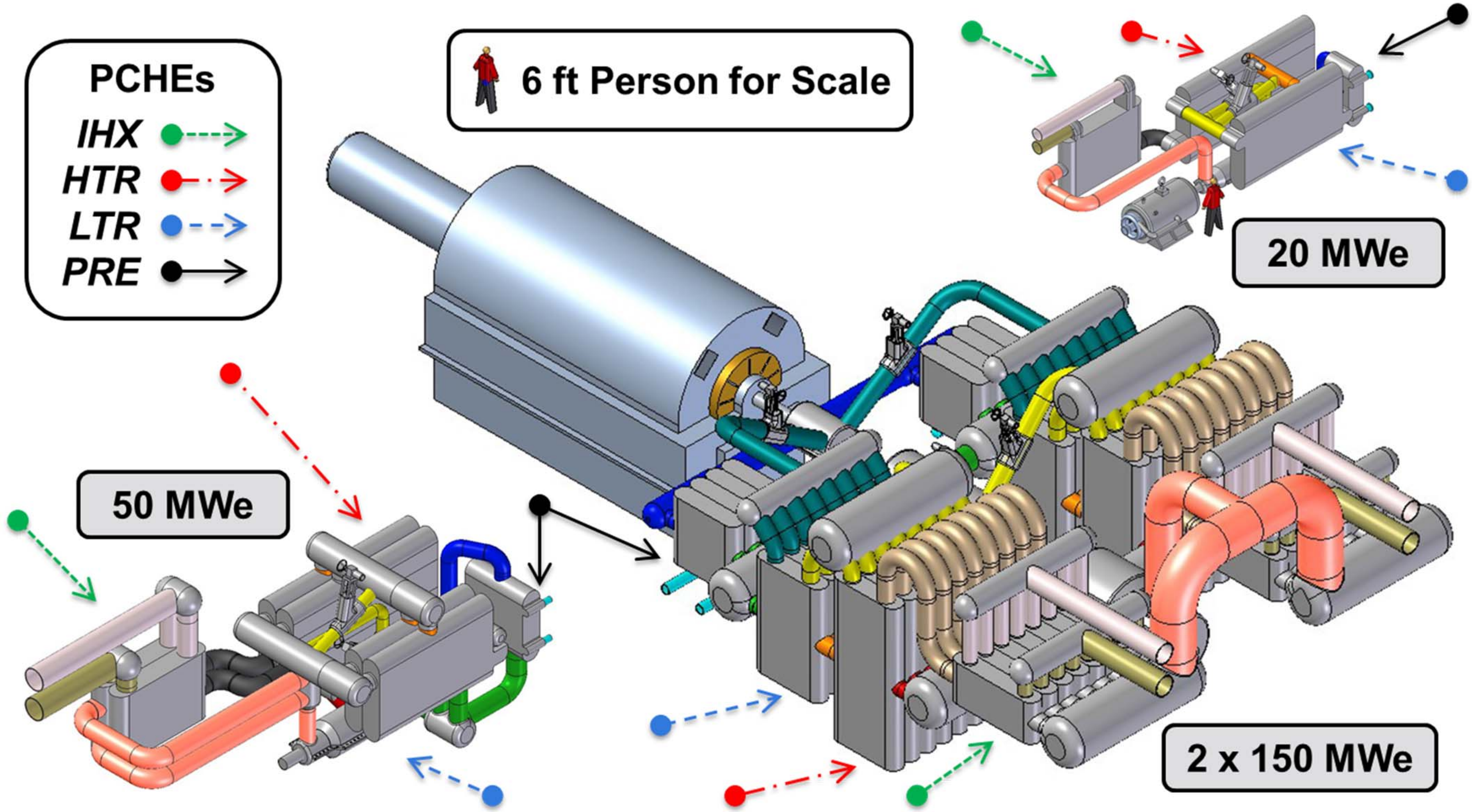
[3]

[1] http://www.co2turbine.com/development-testing.html
[2] Southwest Research Institute and Thar Energy L.L.C., “Novel Supercritical Carbon Dioxide Power Cycle Utilizing Pressurized Oxy-combustion In Conjunction With Cryogenic Compression,” 24-Oct-2012.
[3] Moore, “SunShot Status Update - Supercritical Carbon Dioxide Turbo-Expander and Heat Exchangers.” US DOE, 15-Dec-2012.

Heat Exchangers & Additive Manufacturing

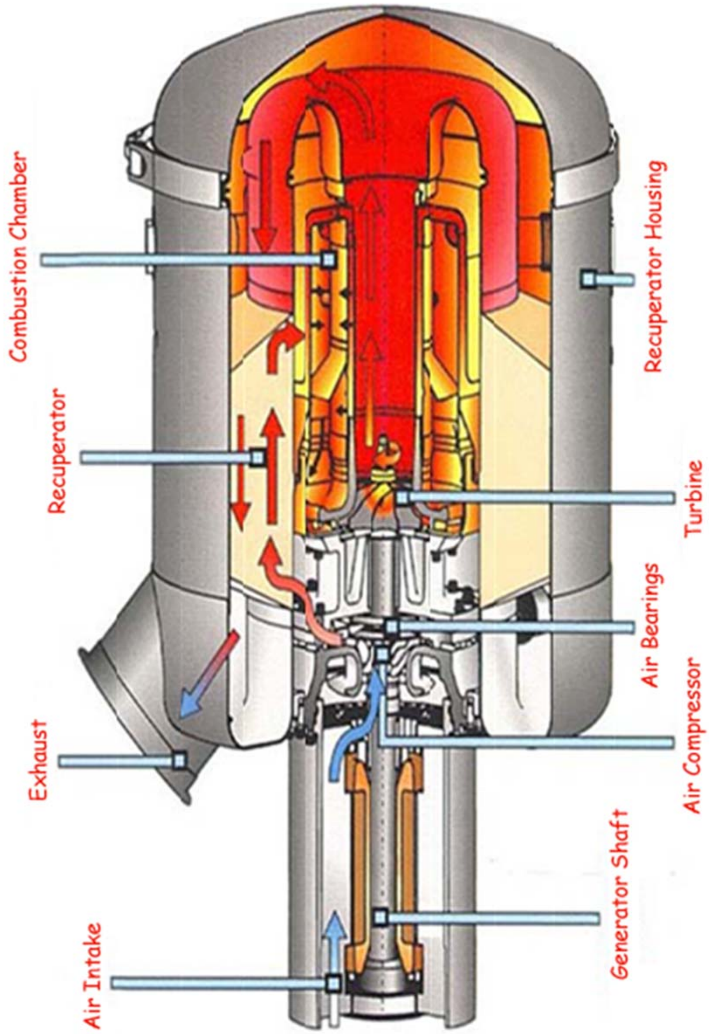
AM HEAT EXCHANGERS AT SANDIA

sCO2 Brayton Heat Exchangers

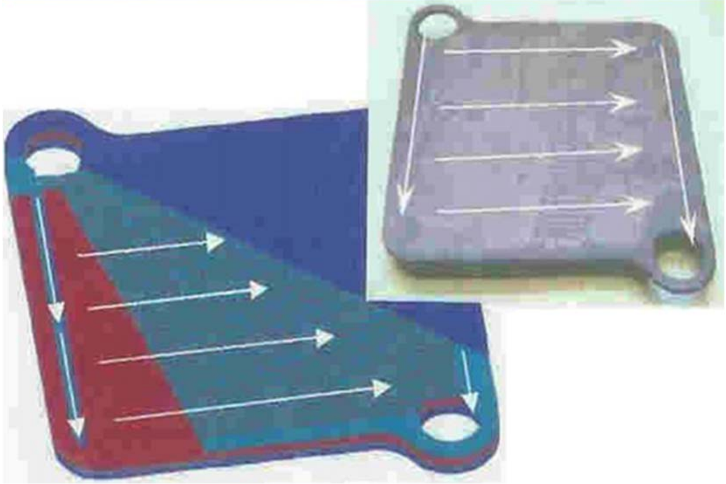


J.P. Gibbs, P. Hejzlar, & M.J. Driscoll. (2006). *Applicability of Supercritical CO2 Power Conversion Systems to GEN IV Reactors* (Topical Report No. MIT-GFR-037) (p. 97). Cambridge, MA: Center for Advanced Nuclear Energy Systems MIT Department of Nuclear Science and Engineering.

High Temperature Microturbines



Capstone Turbine



[2]

[2] C. F. McDonald and C. Rodgers, “Small recuperated ceramic microturbine demonstrator concept,” *Applied Thermal Engineering*, vol. 28, no. 1, pp. 60–74, Jan. 2008.

SNL Cast Metal Heat Exchangers

Sandia National Laboratories

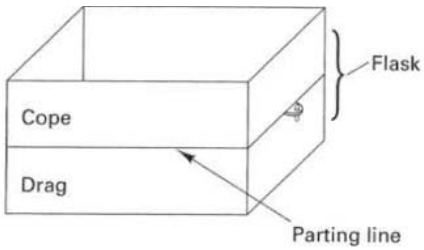
Proposal: Directly cast heat exchanger core geometries.

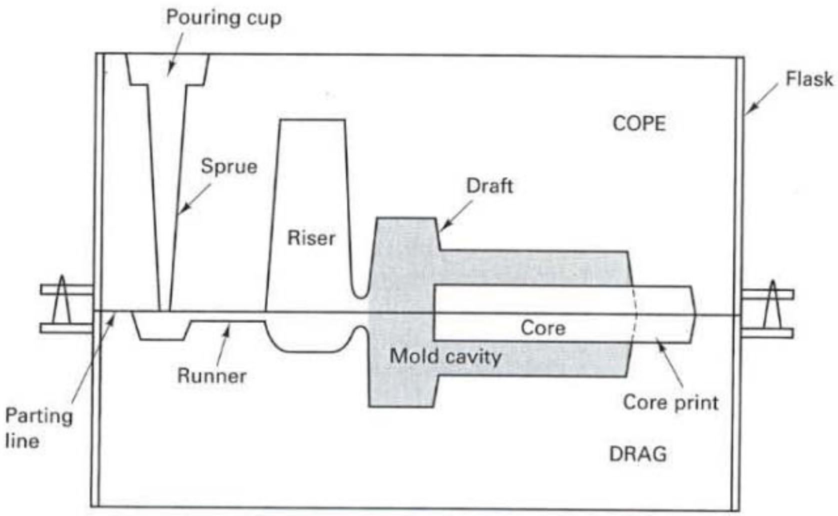
Key Concept: Using inter-connected flow passages provides essential mechanical integrity to casting cores.

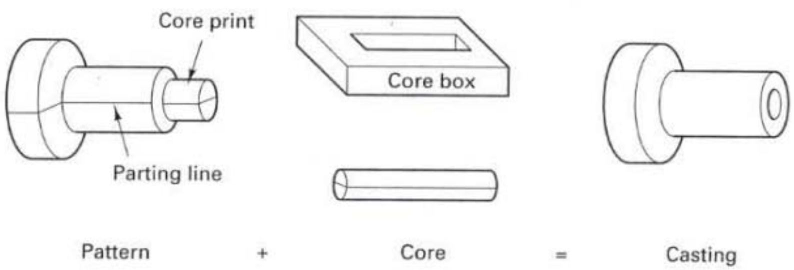
Benefits:

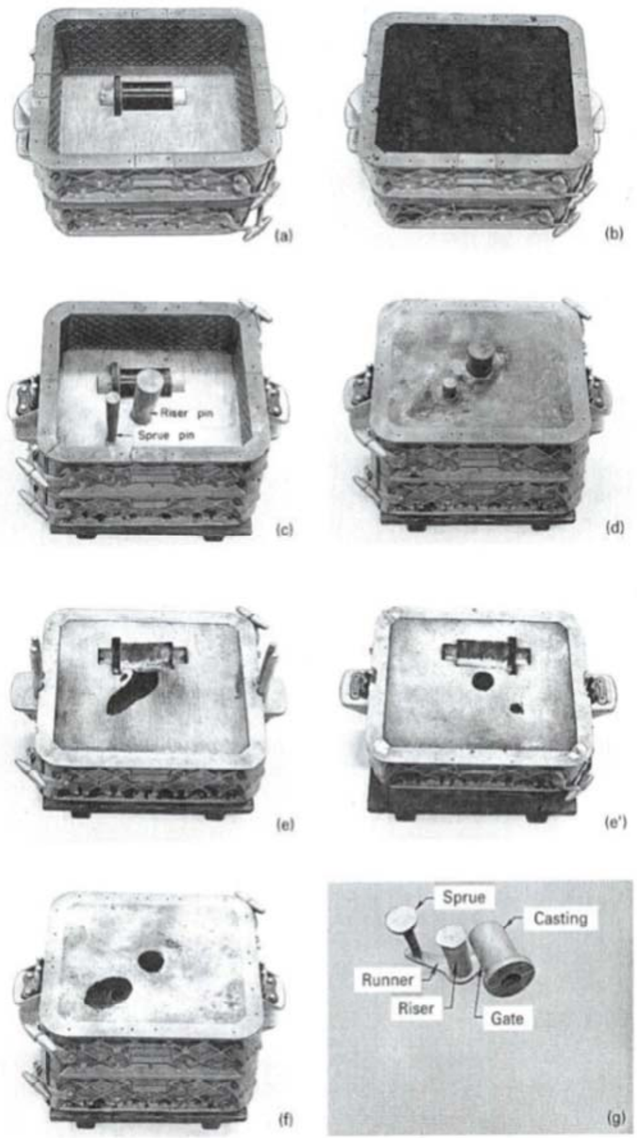
- Reduce cost by as much as a factor of 5
- Reduce lead-time caused high-temperature joining techniques (welding, brazing, bonding)
- Allow for innovative channel geometry
- Greatly expand material possibilities
- Easily incorporate surface features

Basics of Casting and Casting Cores



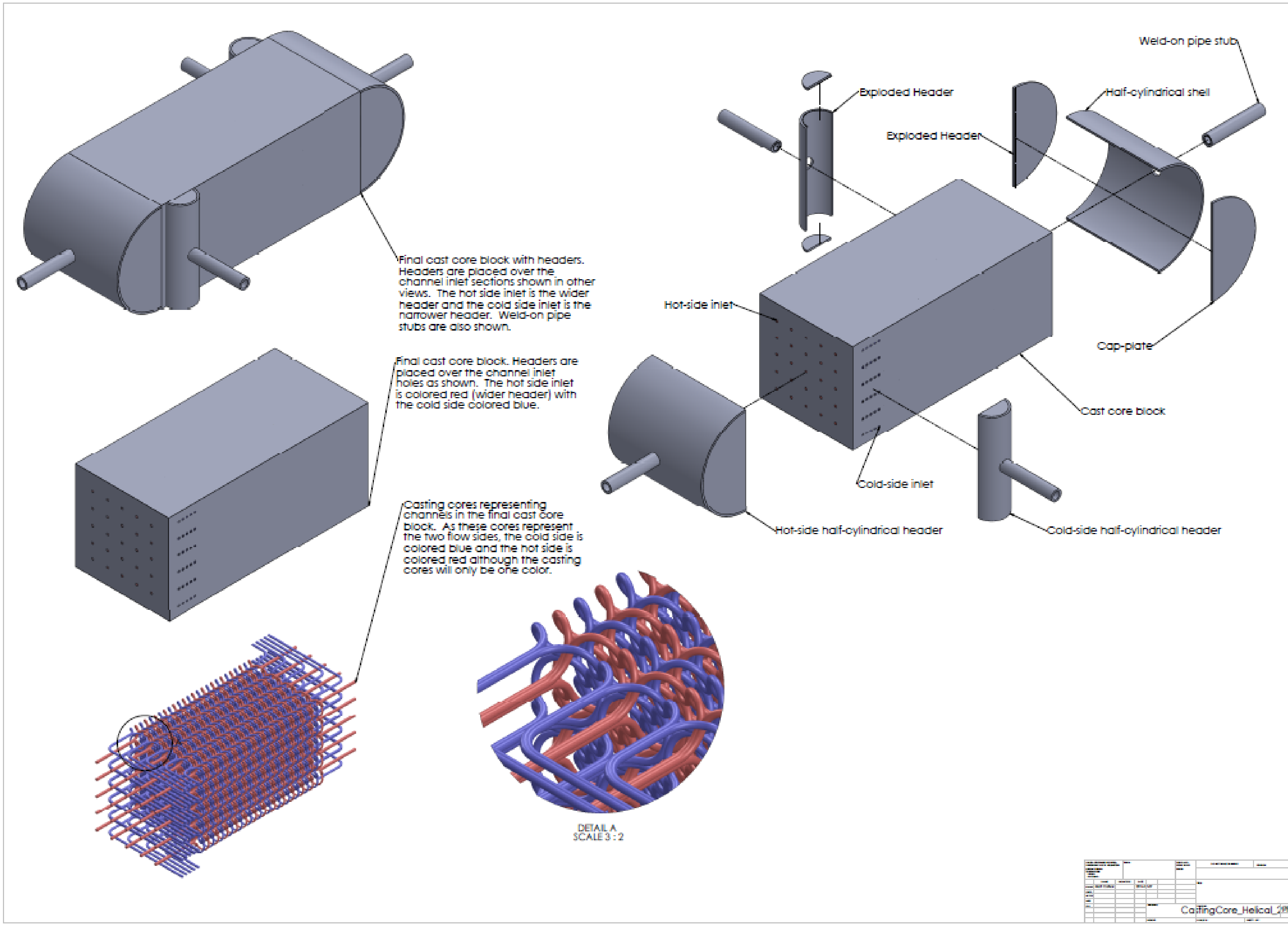




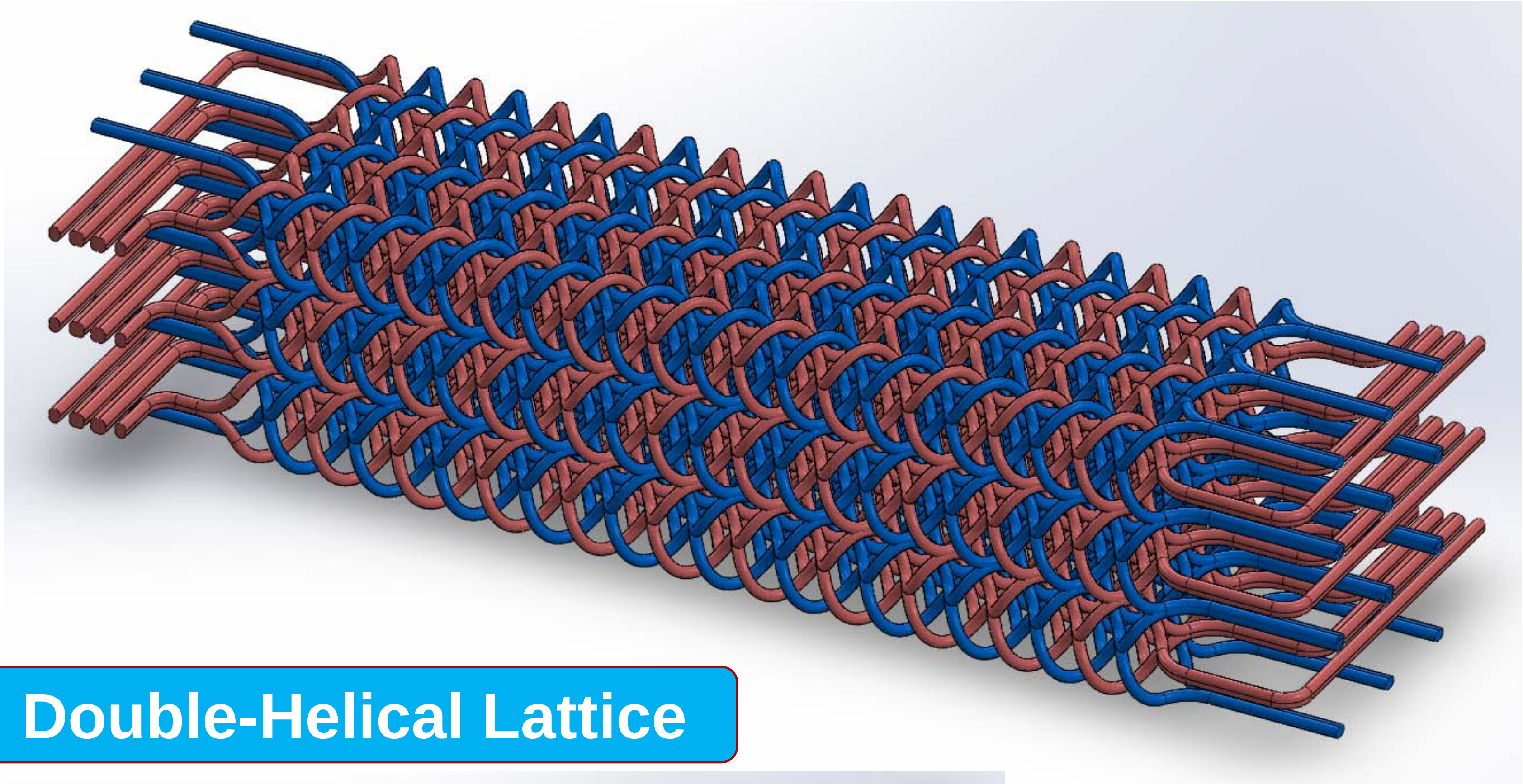


J. T. Black, R. A. Kohser, and E. P. DeGarmo, DeGarmo's materials and processes in manufacturing. Hoboken, NJ: Wiley, 2008.

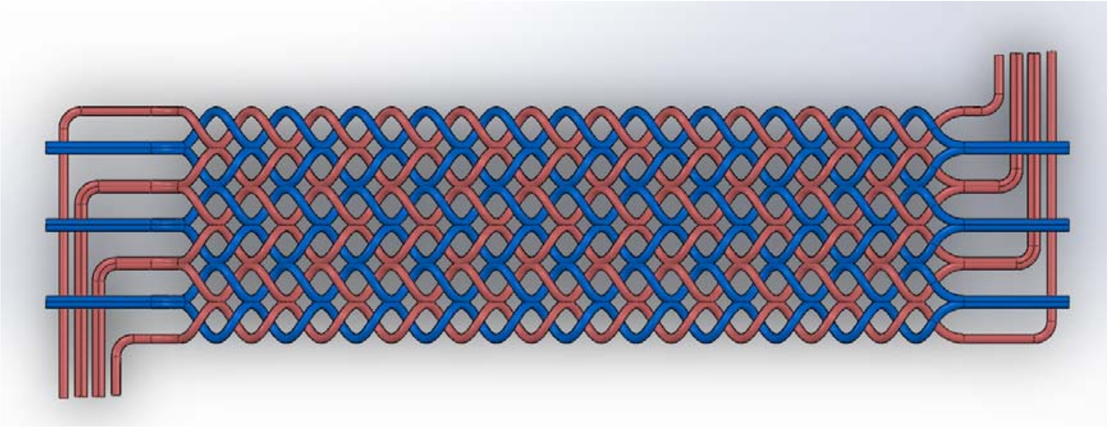
Cast Metal Heat Exchangers

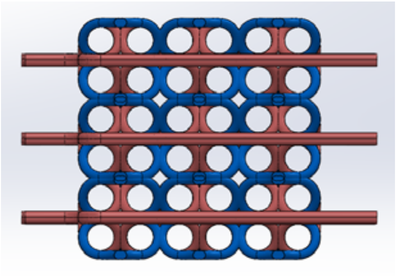


Advanced HXer Geometries



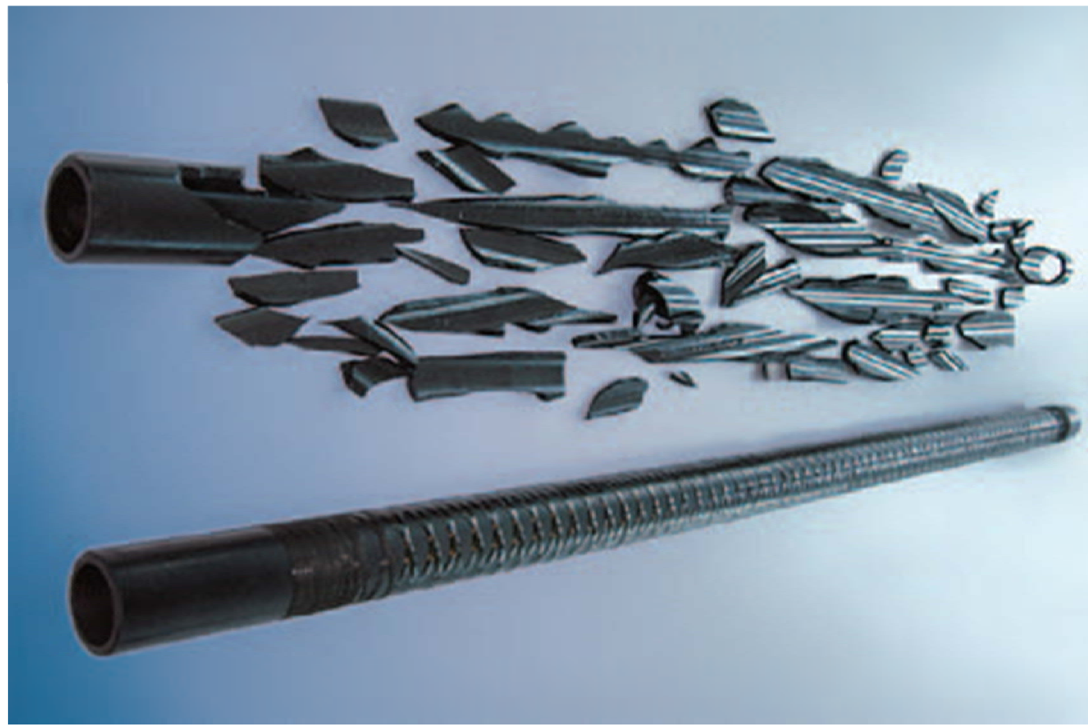
Double-Helical Lattice





Pre-Stressed Ceramic HXers

- Precedence in air intake injection molding process
- Fusible alloy is easy to fabricate and remove
- Fired ceramic is pre-stressed with metal, carbon fiber, or other



[1] K. Fischer, "Materials for the Fusible-Core Technique and Half-Shell Technique," 1991.
[1] SGL Group, "CARBOGUARD Carbon Fiber-Reinforced Process Equipment." SGL Group, 2012.

BACKUP SLIDES

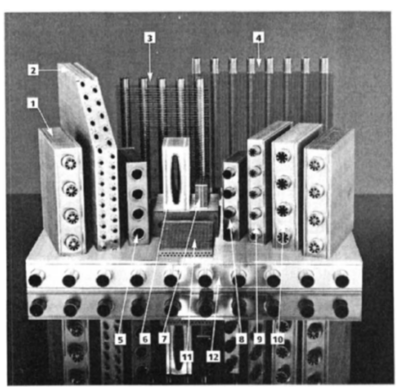
Current Heat Exchanger Types

Sandia National Laboratories

Tube Type

Shell & Tube (S+T)

Coil-Wound Tube



Tube-Fin

Plate Type

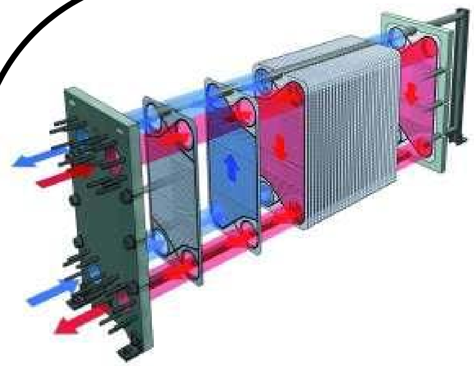


Plate & Frame (PHE)

Hybrid
PCHE/PFHE

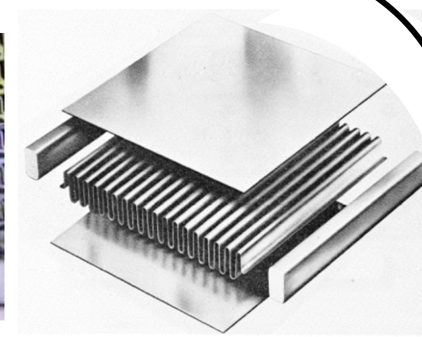
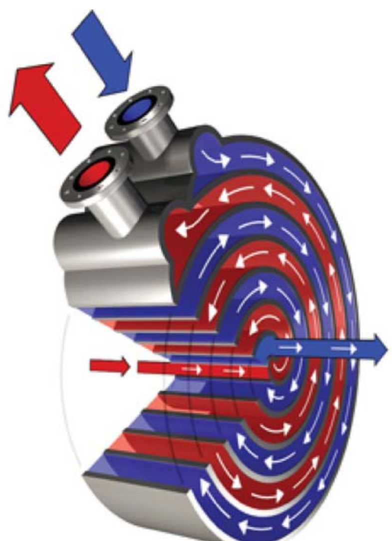
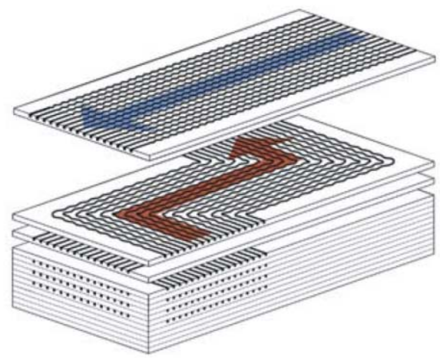


Plate-Fin Heat Exchanger (PFHE)



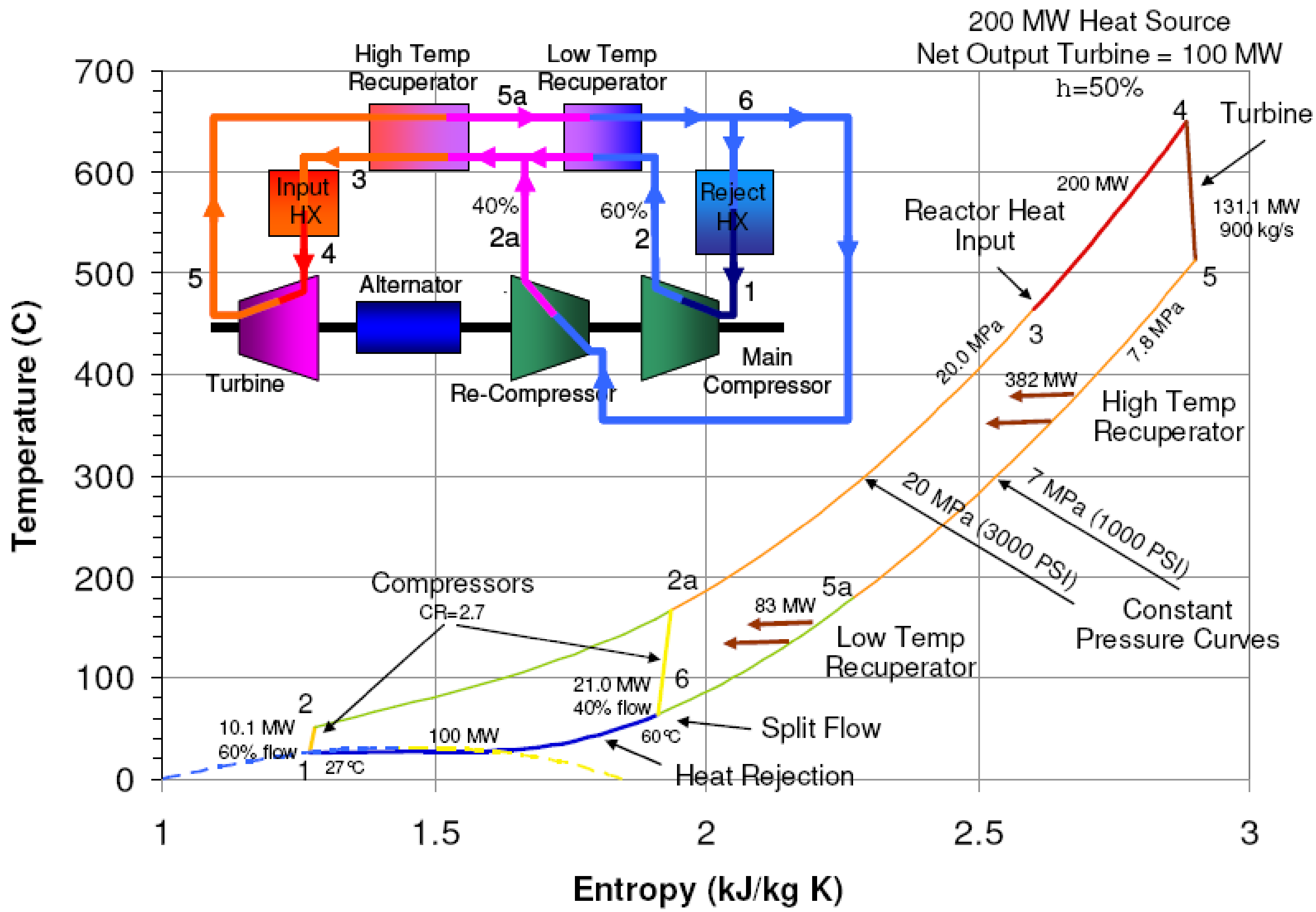
Spiral Plate



Printed-Circuit Heat Exchanger (PCHE)

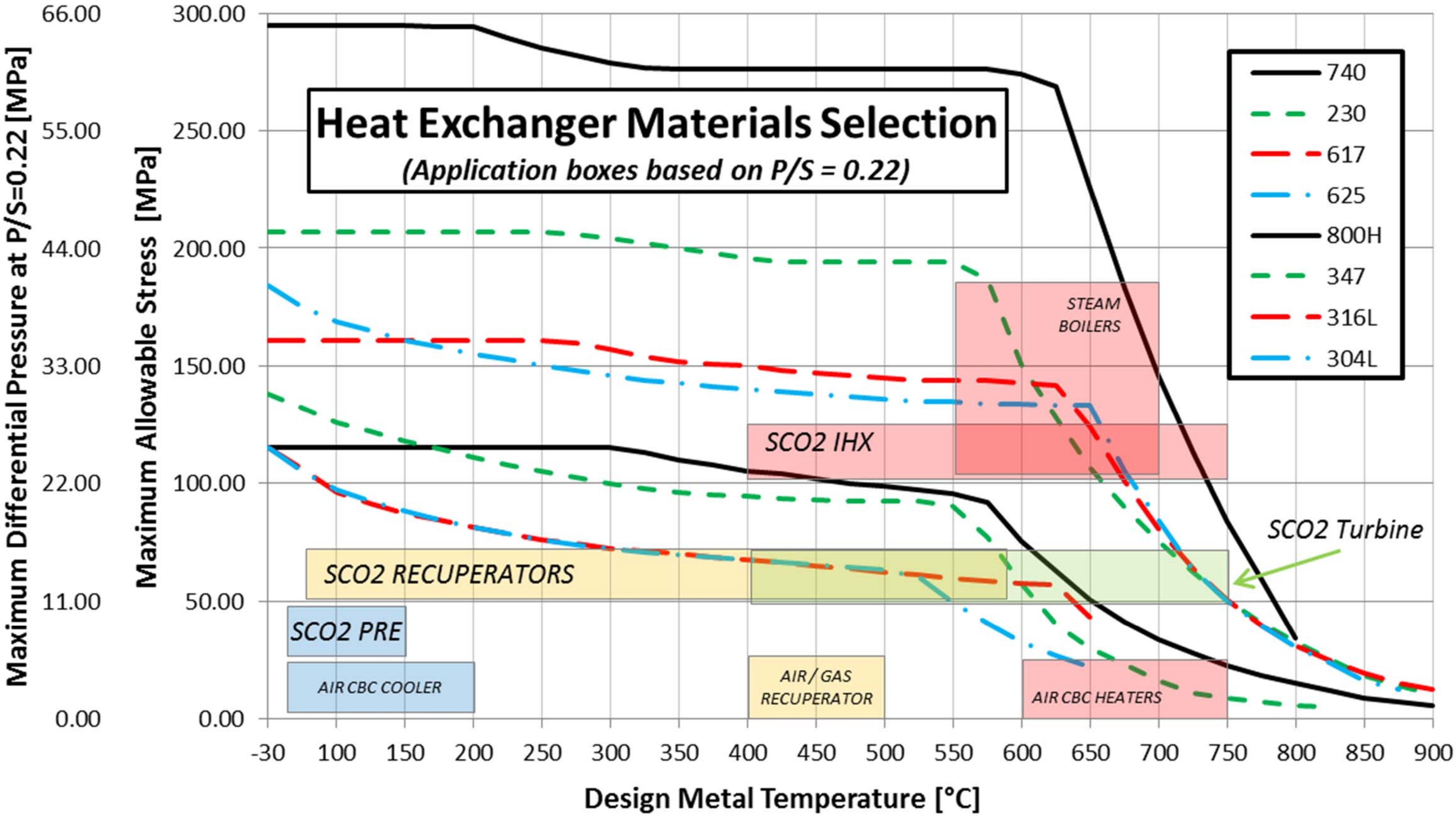
Shell & Plate

Supercritical CO_2 Brayton Cycle



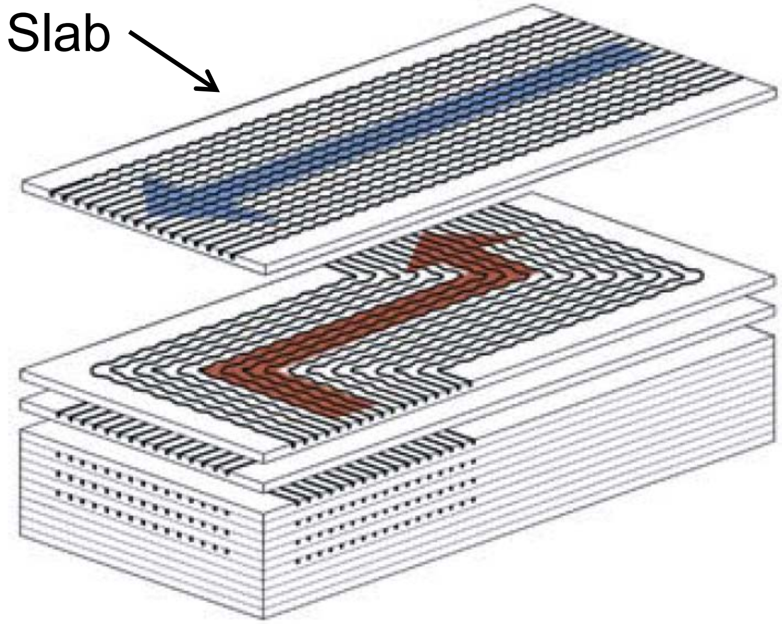
E. J. Parma, S. A. Wright, M. E. Vernon, D. D. Fleming, G. E. Rochau, A. J. Suo-Anttila, A. Al Rashdan, and P. V. Tsvetkov, “Supercritical CO2 Direct Cycle Gas Fast Reactor (SC-GFR) Concept,” Sandia National Laboratories, Albuquerque, NM, USA, SAND 2011-2525, May 2011.

Heat Exchanger Requirements

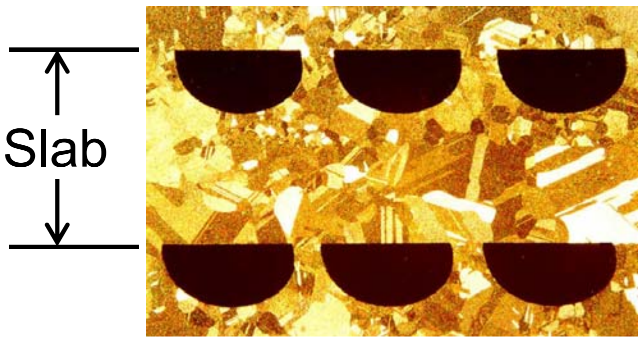


The Printed Circuit Heat Exchanger

Heat Exchanger Core



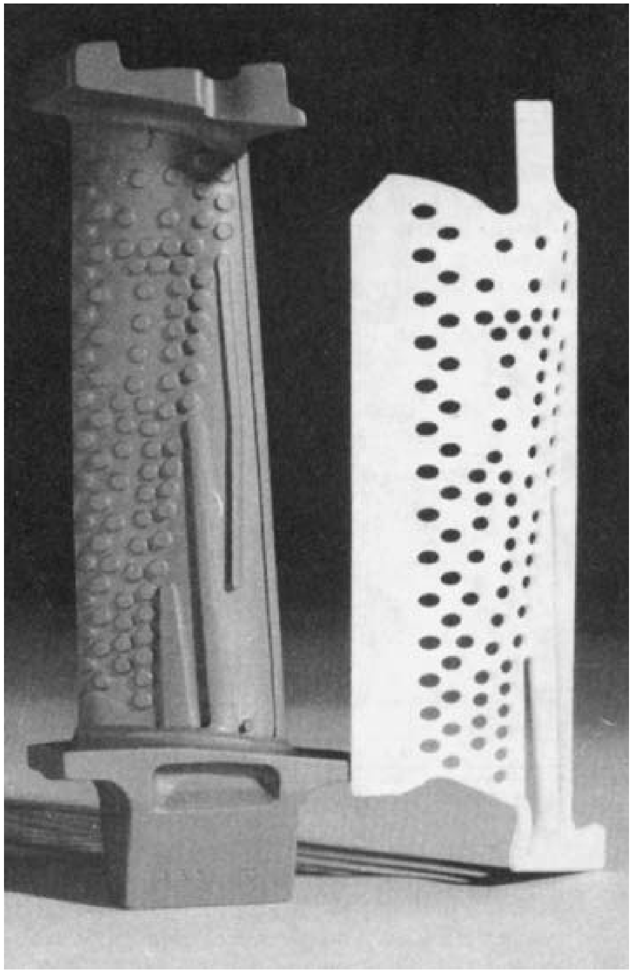
Diffusion Bonding

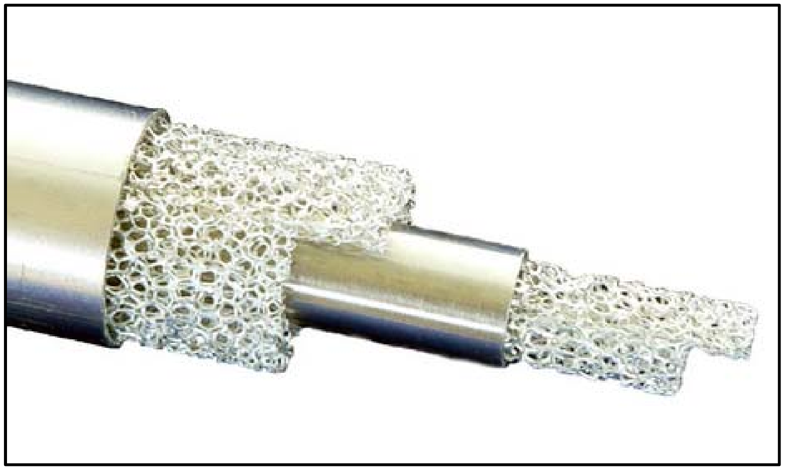


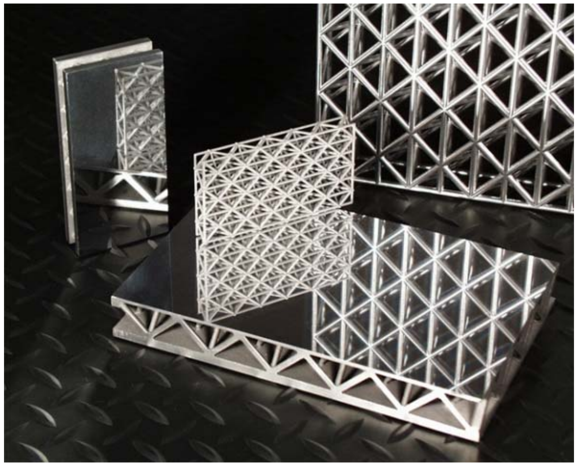
Core and Manifold Assembly

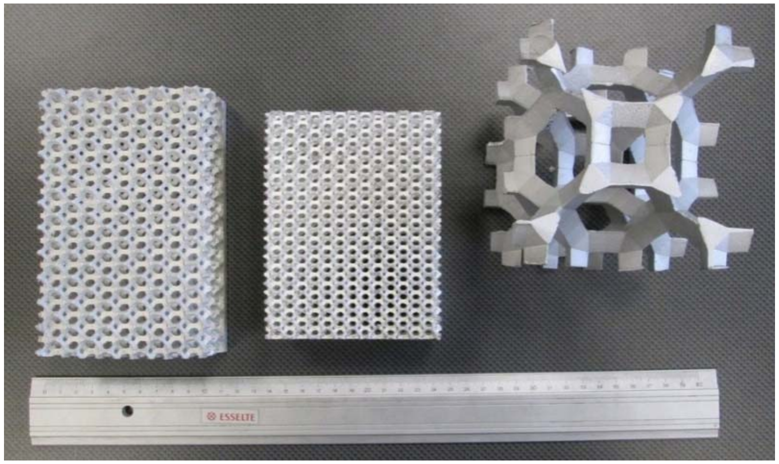
CMHE Industrial Precedent

Sandia National Laboratories



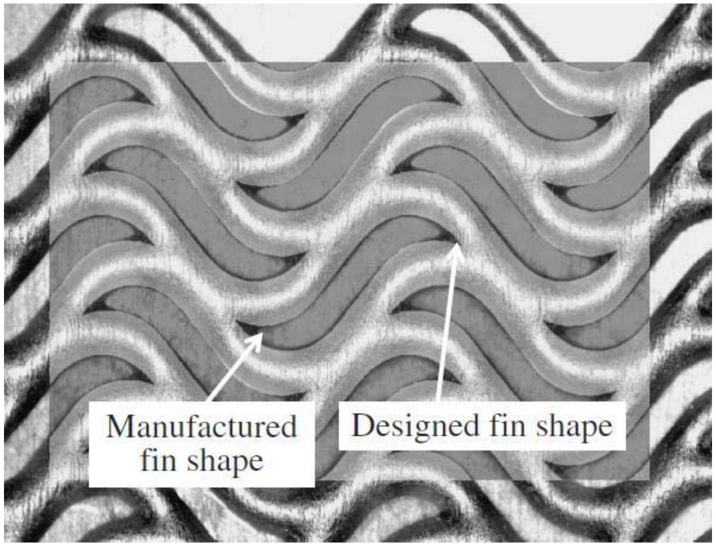


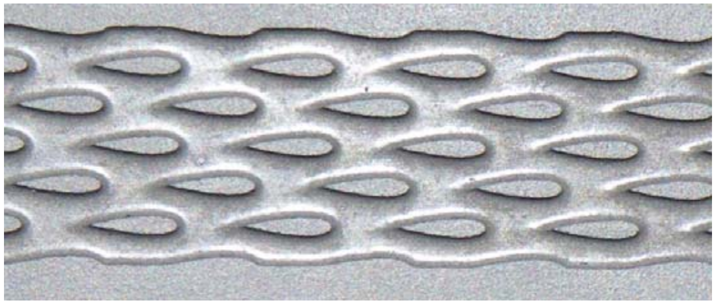


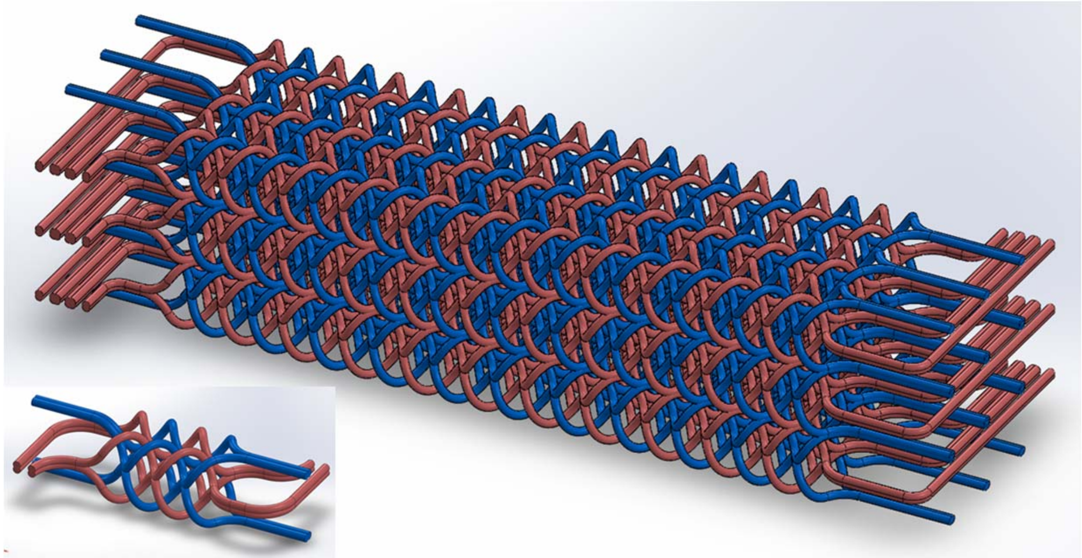


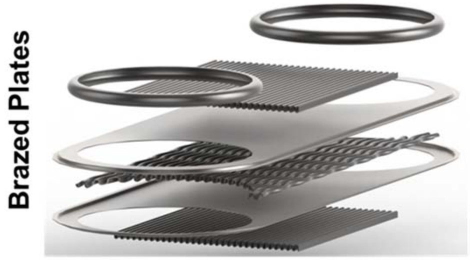
M. J. Donachie, Superalloys a technical guide. Materials Park, OH: ASM International, 2002.
http://www.fedtechgroup.com/advanced_materials/lbs/lbs_cast.html
http://www.ergaerospace.com/project-gallery.htm
http://www.alveotec.fr/nos-actualites/exemples-d-applications-mousses-metalliques_55.html

CMHE Recuperator Geometries







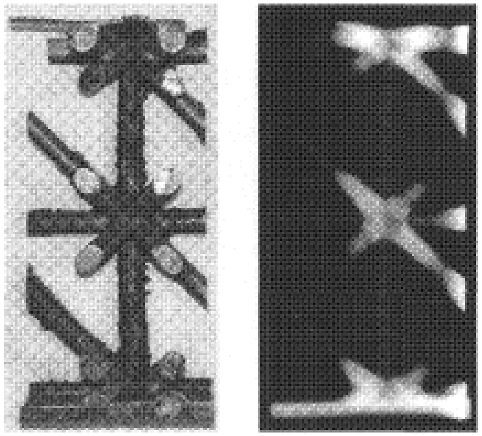


- Requires plate stamping

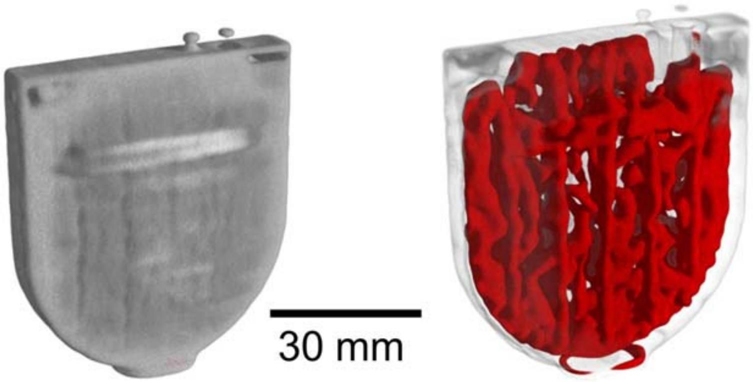
- Dry-fit multiple casting cores

Inspection for Residual Ceramic

X-Ray Radiography

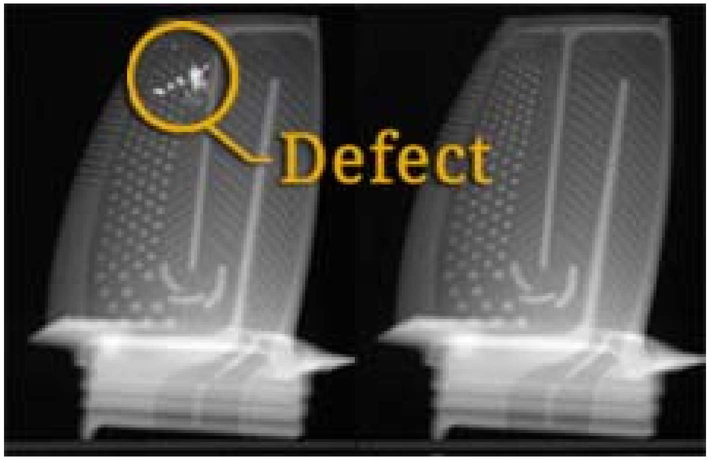


Lattice block material



Microfluidic device

Neutron Radiography

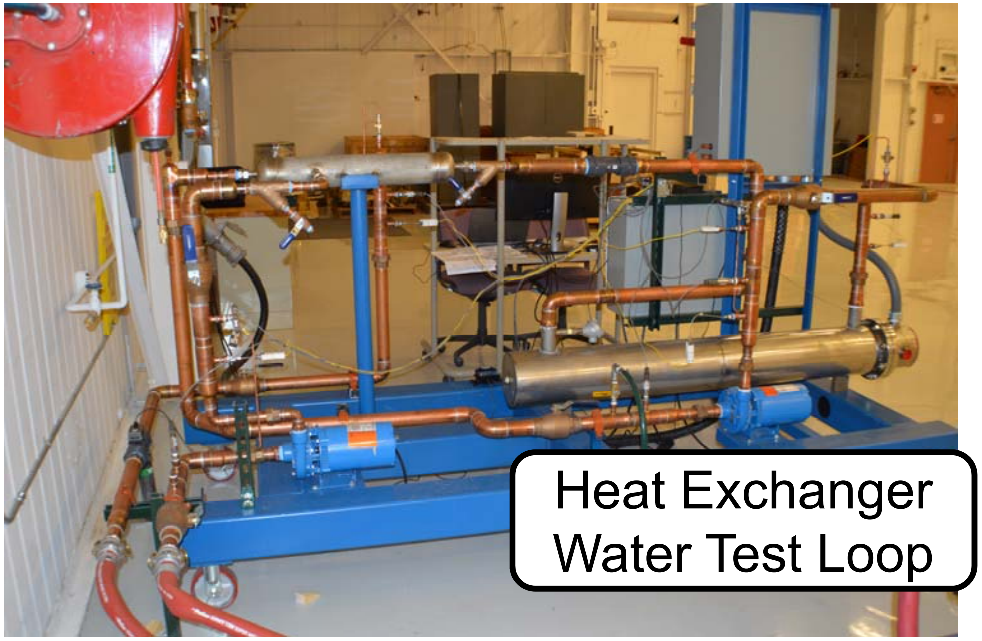


Turbine airfoil

Automotive transmission manifold

Testing of Prototype Equipment

The Nuclear Energy Systems Laboratory (NESL) has capabilities to test heat exchangers with gases, liquids, and refrigerants.



Heat Exchanger Water Test Loop

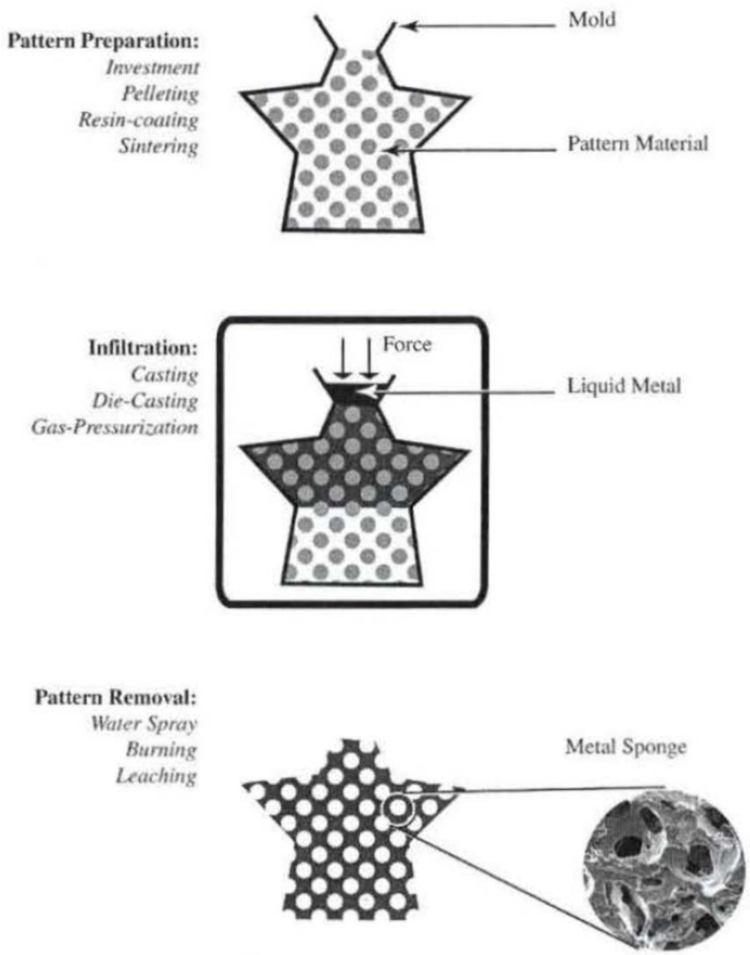
sCO2 Natural Circulation Loop

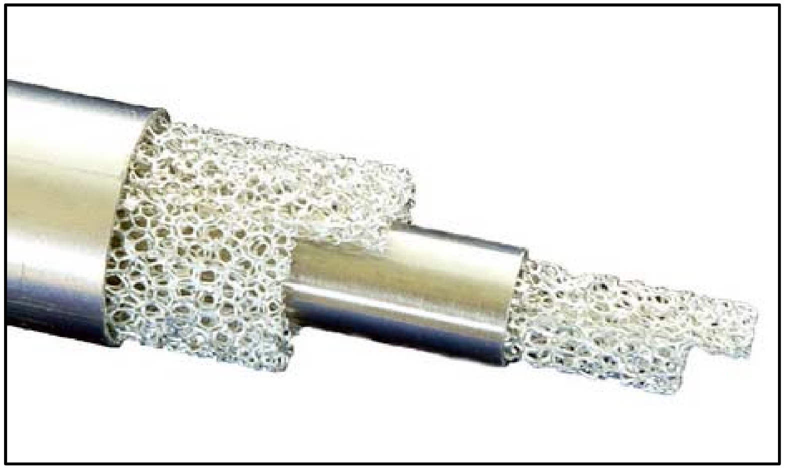
Air Brayton Loop

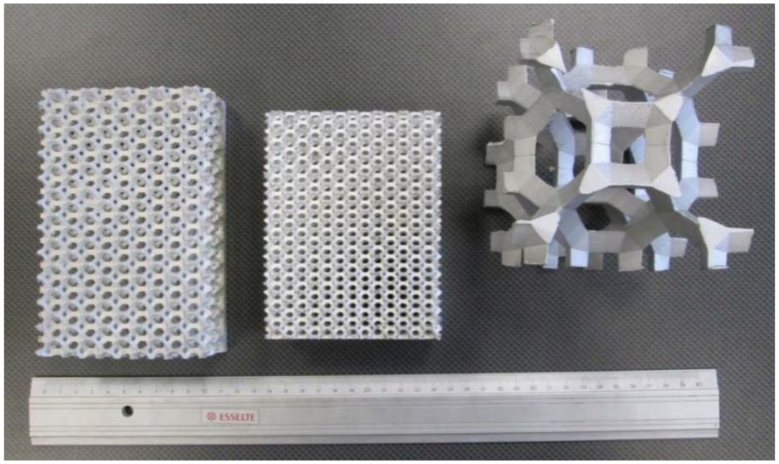
Compressor Loop

sCO2 Brayton Loop

Industrial Precedent







Handbook of Cellular Metals: Production, Processing, Applications. Weinheim: Wiley-VCH, 2002.

Approximate Cost Scaling

$$Cost = C_{ESDU} F_{mat} F_p F_i UA_{sp} P_{elec}$$

C_{ESDU} is the UA-specific cost value [$/(kW/K)]

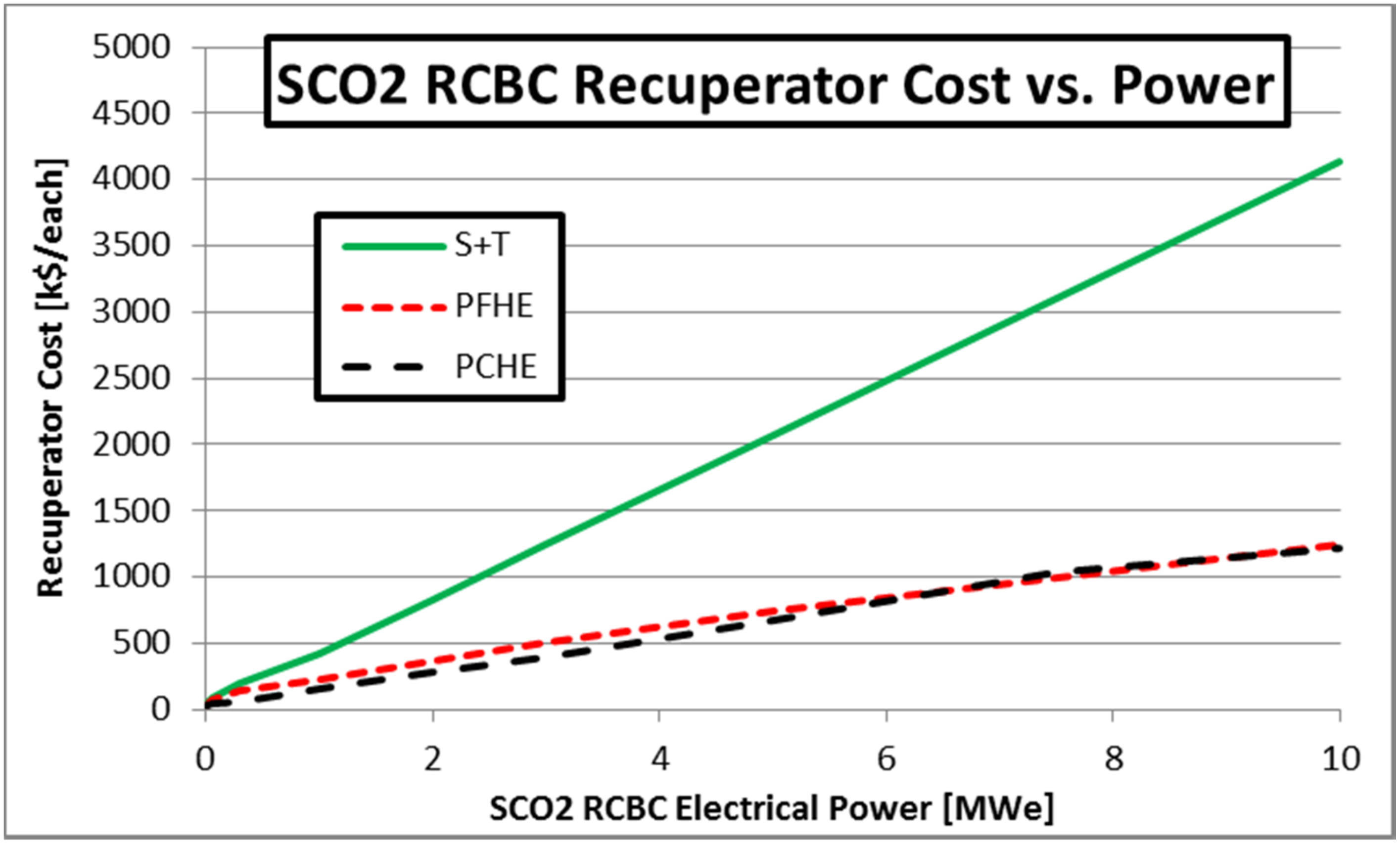
F_{mat} is a material cost factor

F_P is a pressure cost factor

F_i is an adjustment for inflation

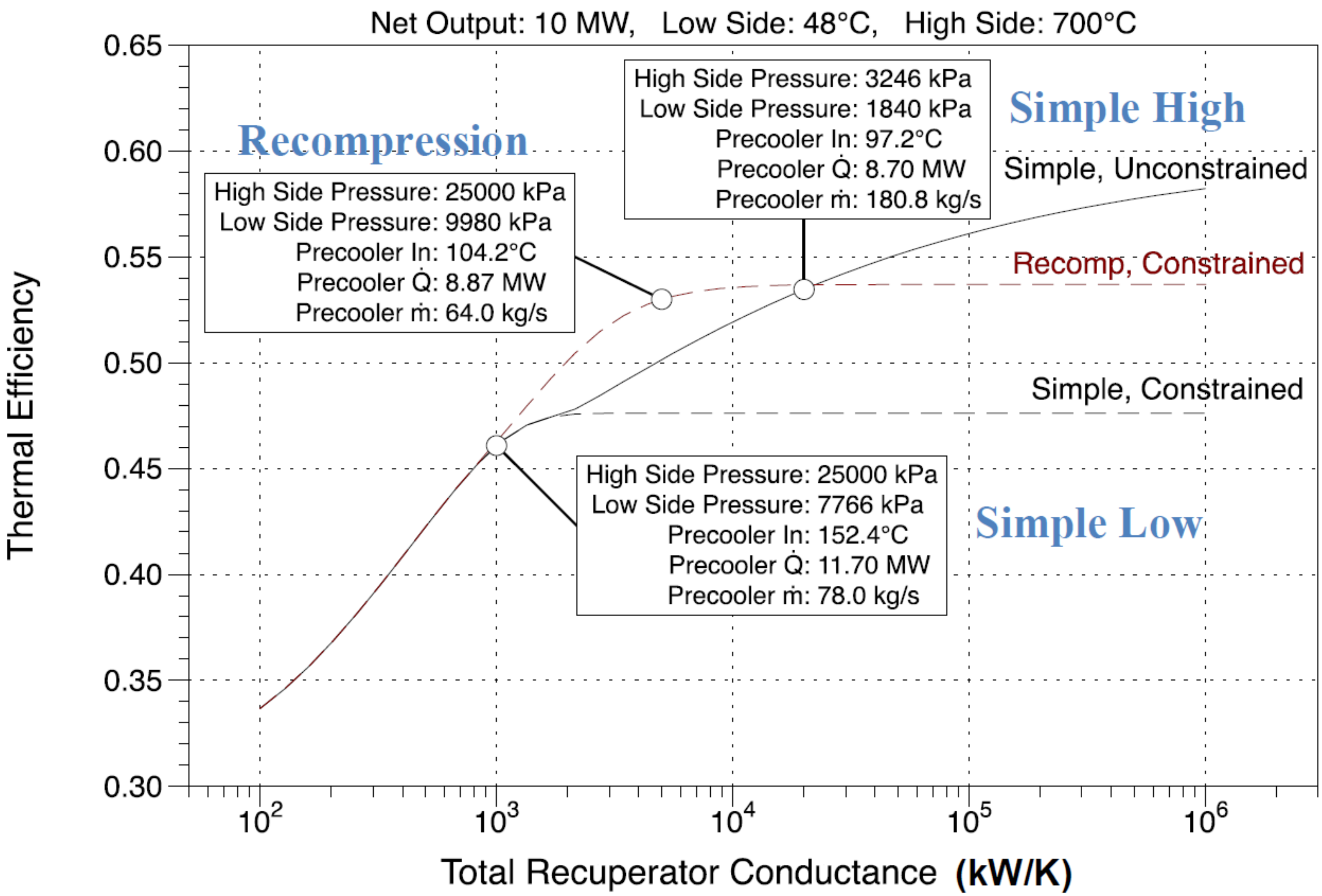
UA_{sp} is the cycle power-specific UA [kW/(K-MWe)]

P_{elec} is the cycle power level [MWe]



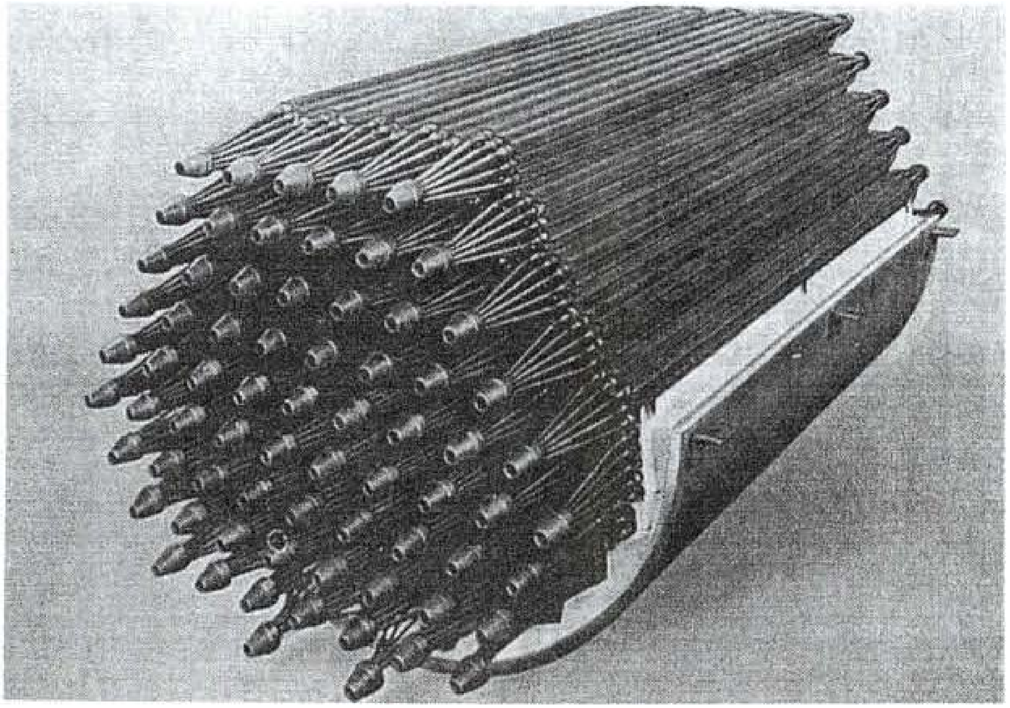
ESDU, "Selection and Costing of Heat Exchangers," Engineering Sciences Data Unit, ESDU 92013, Dec. 1994.

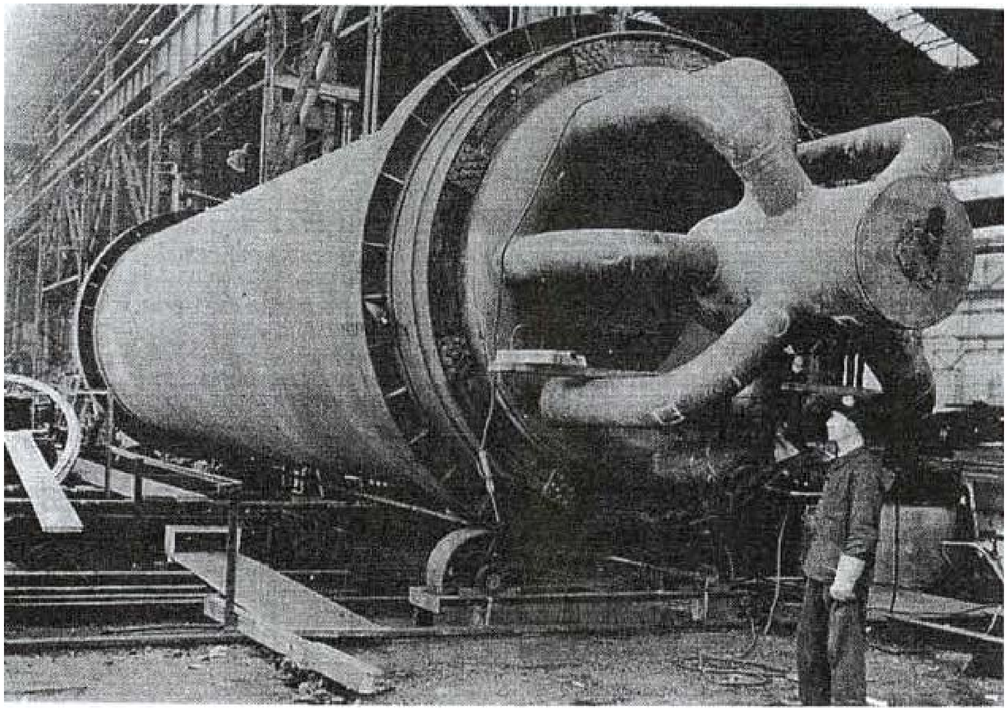
Recuperation in Brayton Cycles



Dyreby, J., S. Klein, G. Nellis, and D. Reindl. (2012). Development of Advanced Models for Supercritical Carbon Dioxide Power Cycles for use in Concentrating Solar Power Systems. National Renewable Energy Laboratory.

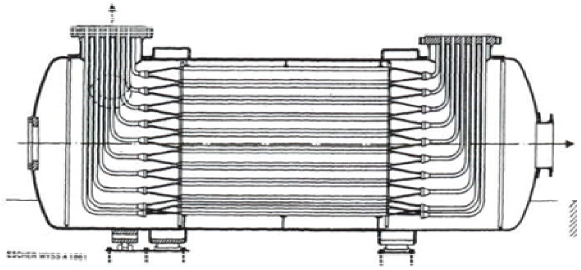
Early Air CBC Recuperators

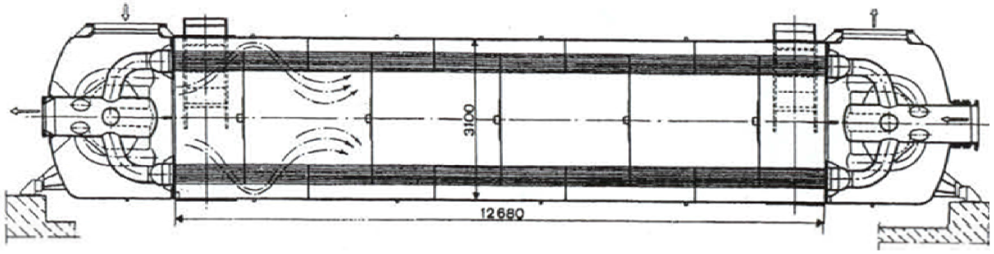




2 to 6 MWe Plant Style

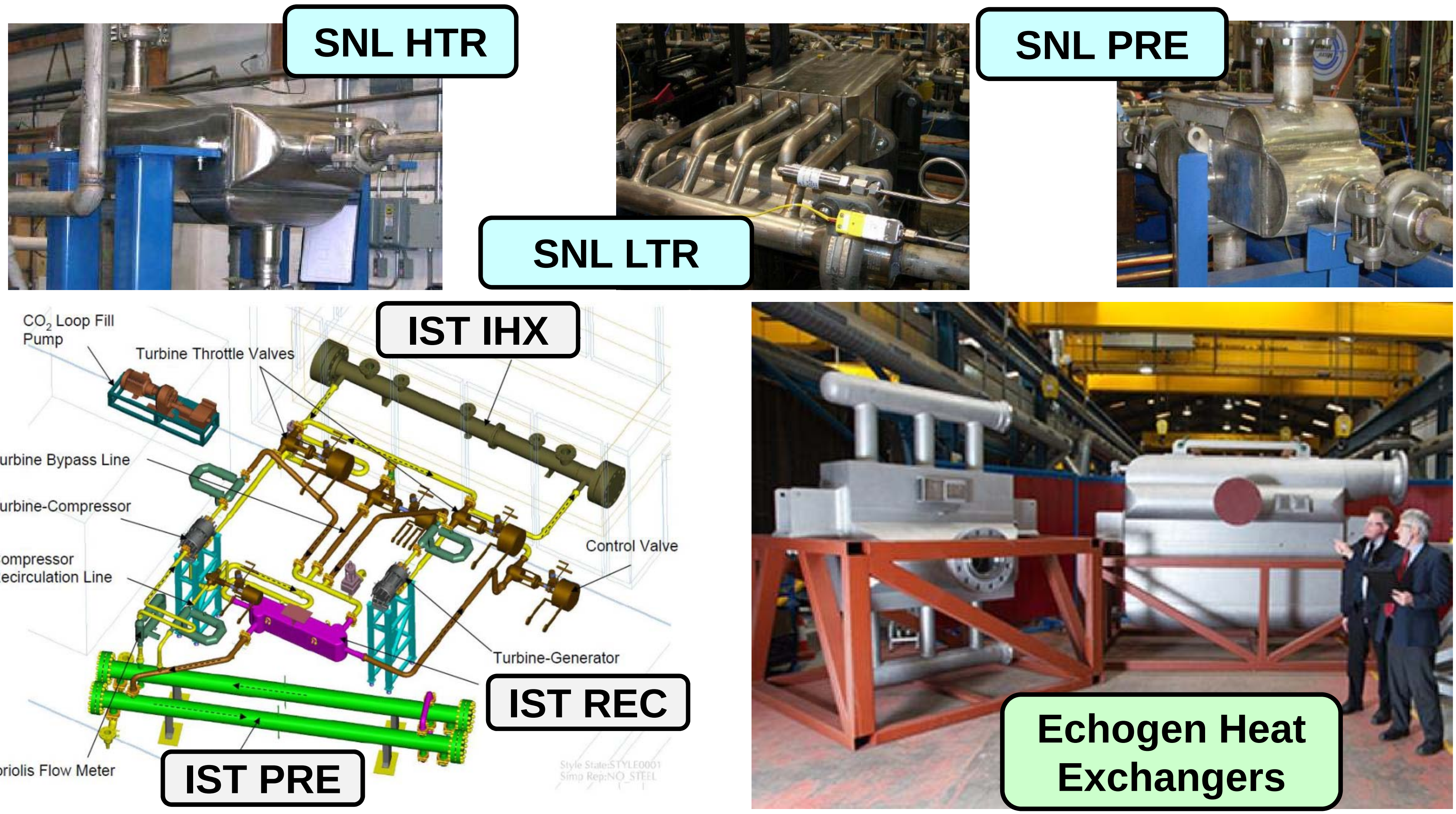
12 to 30 MWe Plant Style





H. U. Frutschi, Closed-cycle gas turbines : operating experience and future potential. New York: ASME Press, 2005.

Current SCO2 CBC HXers



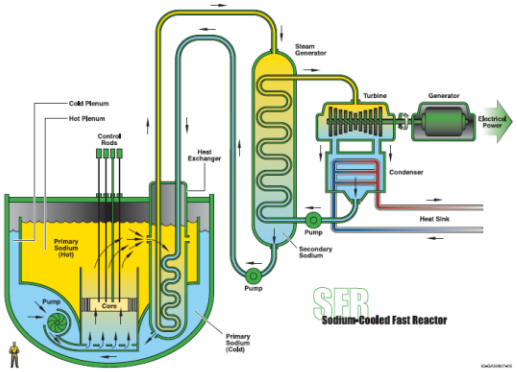
G. O. Musgrove, C. Pittaway, D. Shiferaw, and S. Sullivan, "Tutorial: Heat Exchangers for Supercritical CO2 Power Cycle Applications," San Antonio, Texas, USA, 03-Jun-2013.

Potential Applications

Coal / Nuclear
Steam Rankine

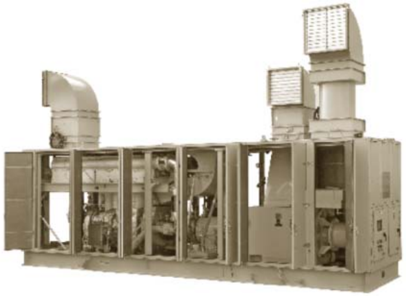
MARINE
Rolls-Royce WR-21
Type 45 Destroyer

VEHICULAR
Honeywell AGT1500
M1 Abrams Tank



GenIV Nuclear
Sodium Fast Reactor

Refrigeration
Commercial, Cryogenic



STATIONARY
Solar Turbines
Mercury 50