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Sandia Progress on Advanced Heat Exchangers for SCO2 Brayton Cycles

The 4th International Symposium – Supercritical CO2 Power Cycles

September 9-10, 2014, Pittsburgh, Pennsylvania

*Carlson, M. D, Kruizenga, A. K., Schalansky, C., Fleming, D. F.

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Overview – SCO2 Cycle Exchangers

- **Several supercritical carbon dioxide (SCO2) cycles proposed**
  - Proposed as an alternative to steam and organic Rankine systems
  - Offer high efficiency, compact turbomachinery, fluid compatibility
  - Recompression Brayton cycles are well-matched to nuclear applications

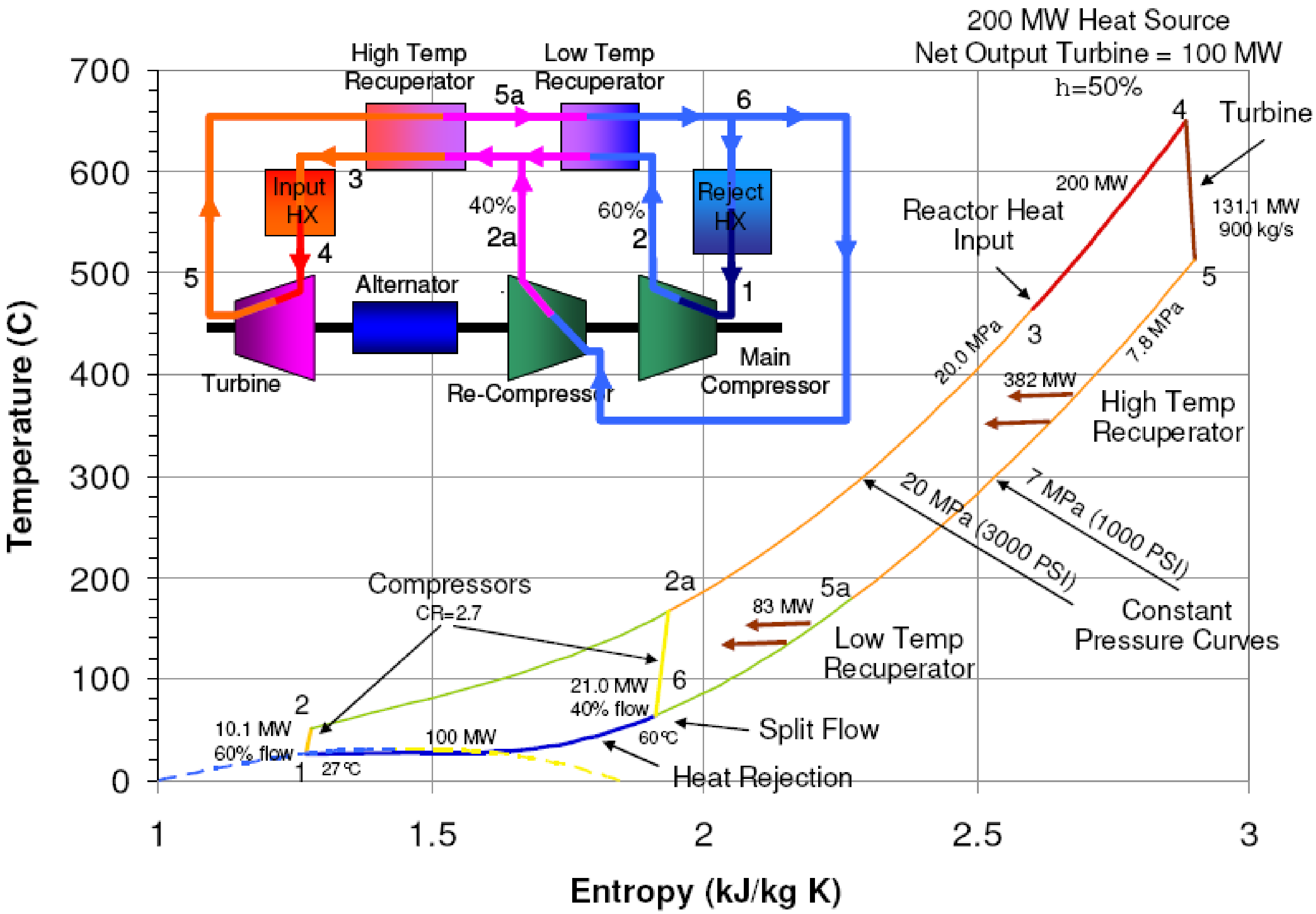
- **Proposed SCO2 cycles are highly recuperated to enhance efficiency**
  - Recuperation between 1 and 5 times the net electrical power
  - Require a combination of high temperature and pressure capability
  - Will be a significant portion of demonstration and production cycles

- **Key requirements are pressure containment and cost scalability**
  - Several types can contain high pressures (PFHE, PCHE, S+T)
  - Current SCO2 test systems use PCHEs almost exclusively
  - Cost and size scaling suggest S+T units are impractical, despite wide use

- **Heat Exchanger Developments at SNL**
  - Partnering with Vacuum Process Engineering to understand PCHEs
  - Developing cast metal heat exchangers (CMHEs) to reduce cost

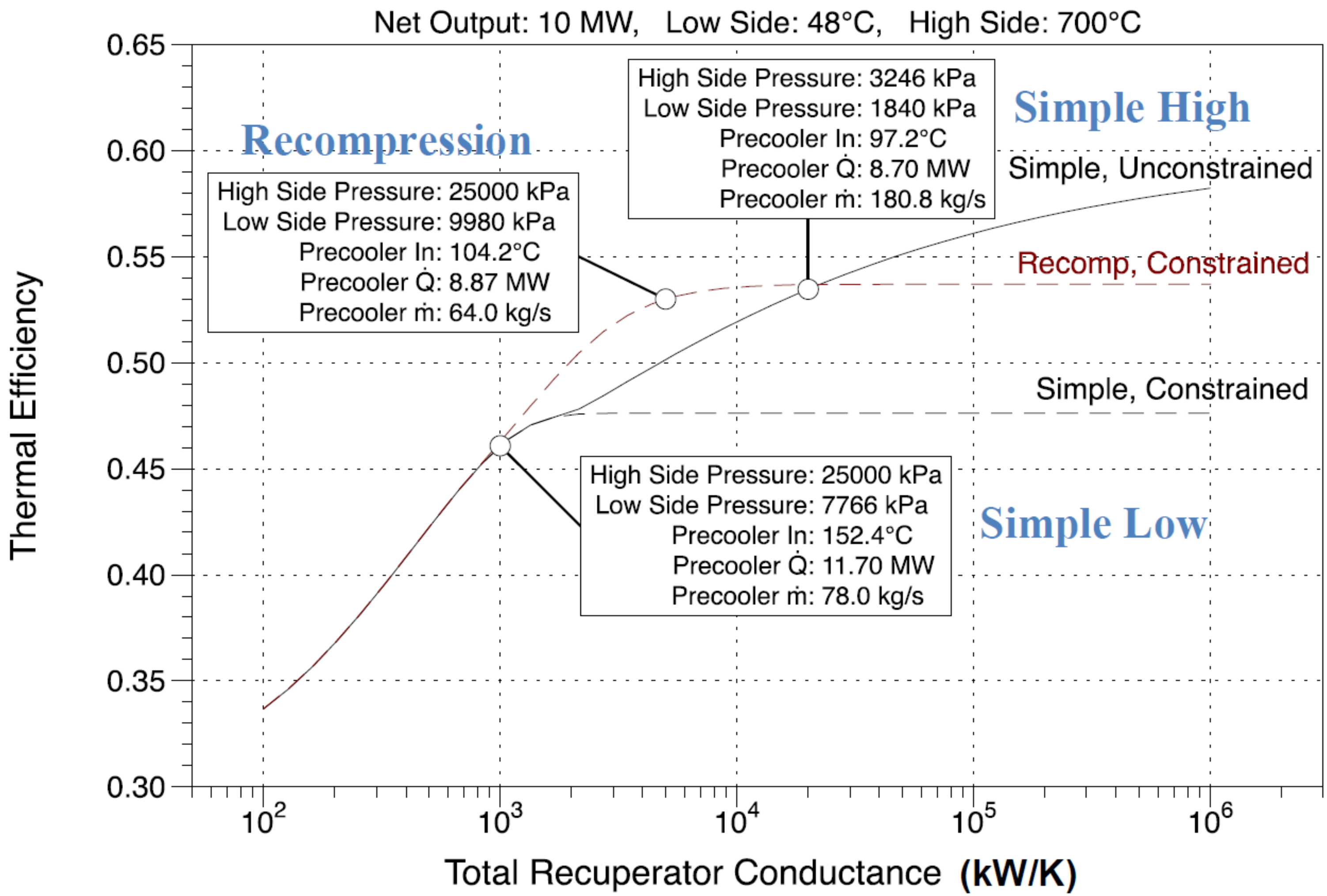
HEAT EXCHANGER BACKGROUND

Supercritical CO_2 Brayton Cycle



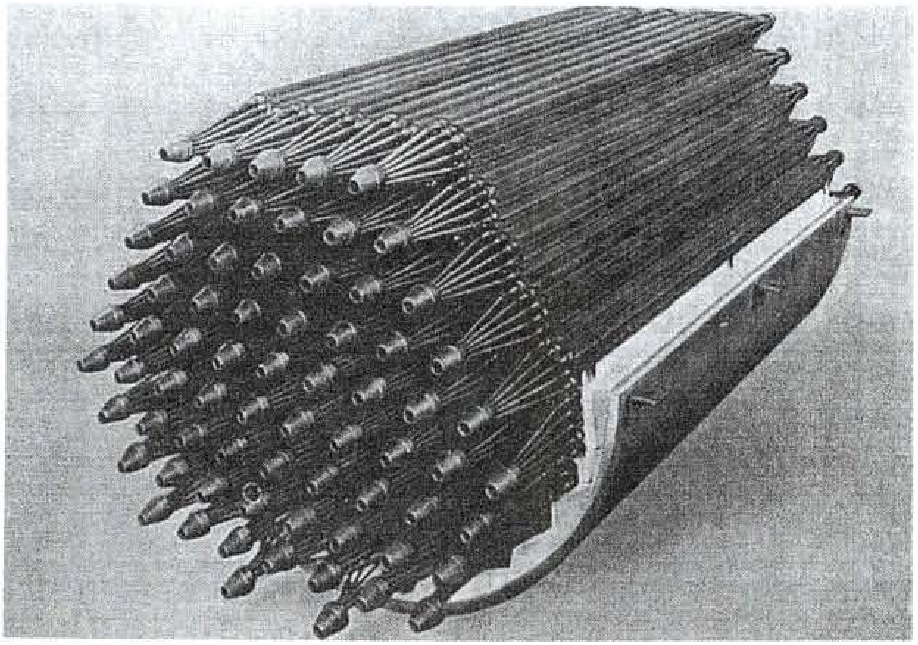
E. J. Parma, S. A. Wright, M. E. Vernon, D. D. Fleming, G. E. Rochau, A. J. Suo-Anttila, A. Al Rashdan, and P. V. Tsvetkov, “Supercritical CO2 Direct Cycle Gas Fast Reactor (SC-GFR) Concept,” Sandia National Laboratories, Albuquerque, NM, USA, SAND 2011-2525, May 2011.

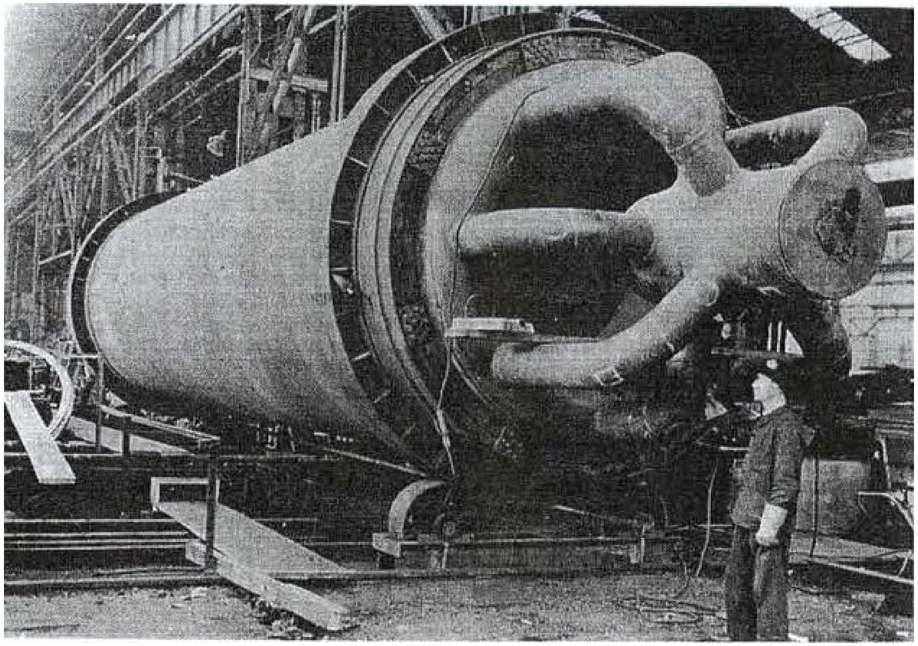
Recuperation in Brayton Cycles



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.

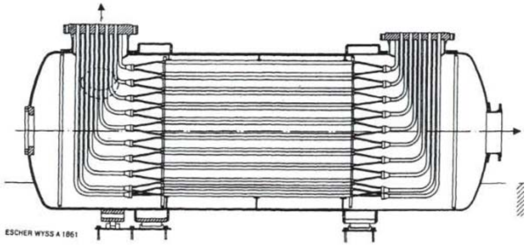
Early Air CBC Recuperators

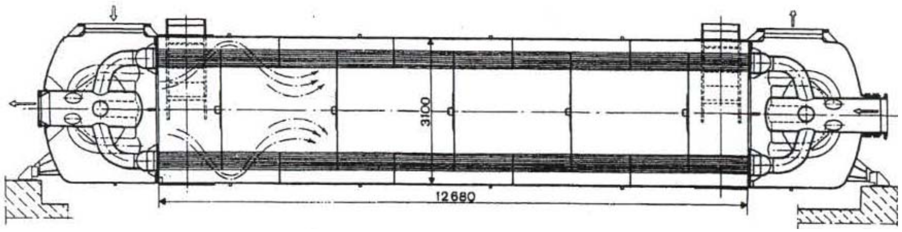




2 to 6 MWe Plant Style

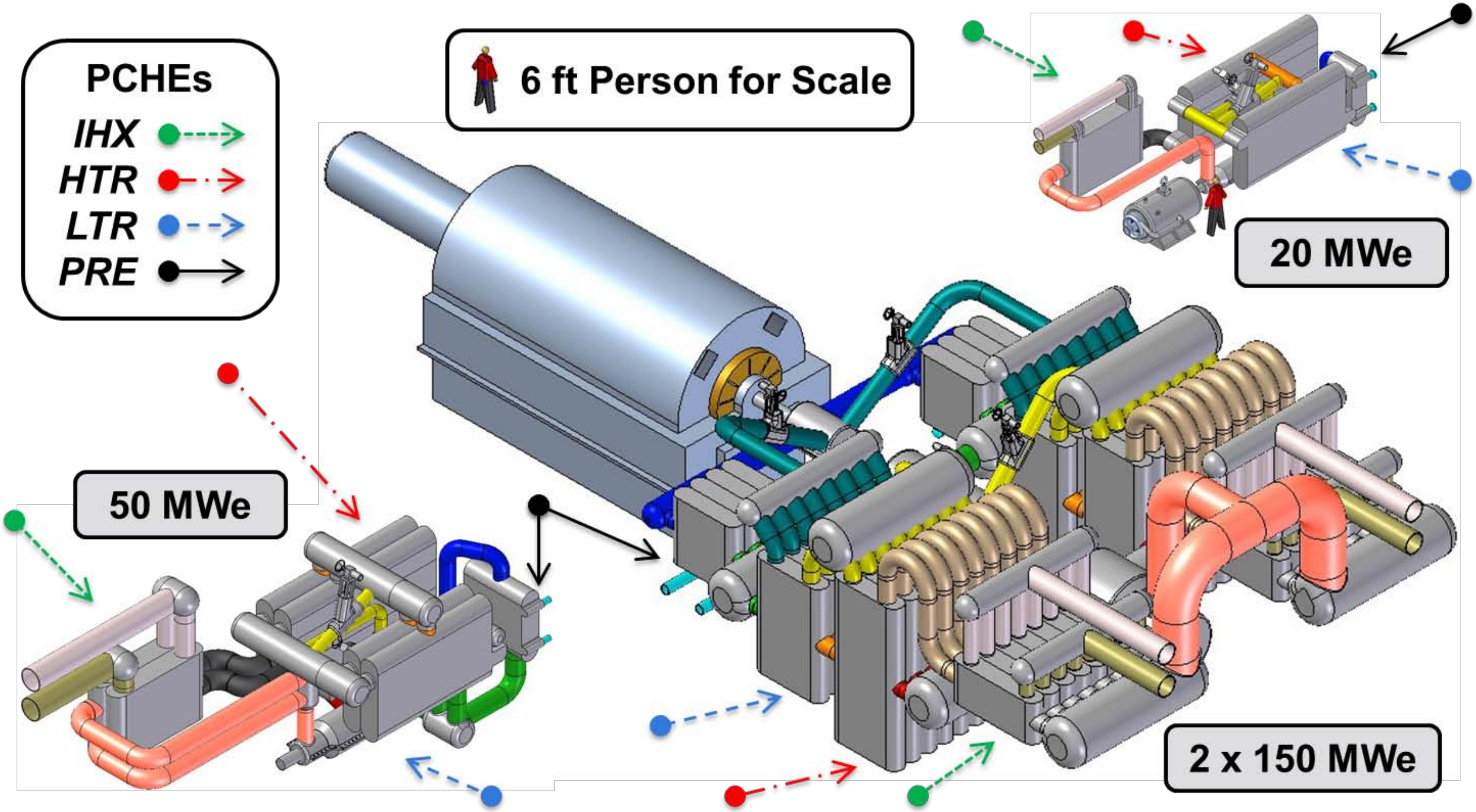
12 to 30 MWe Plant Style





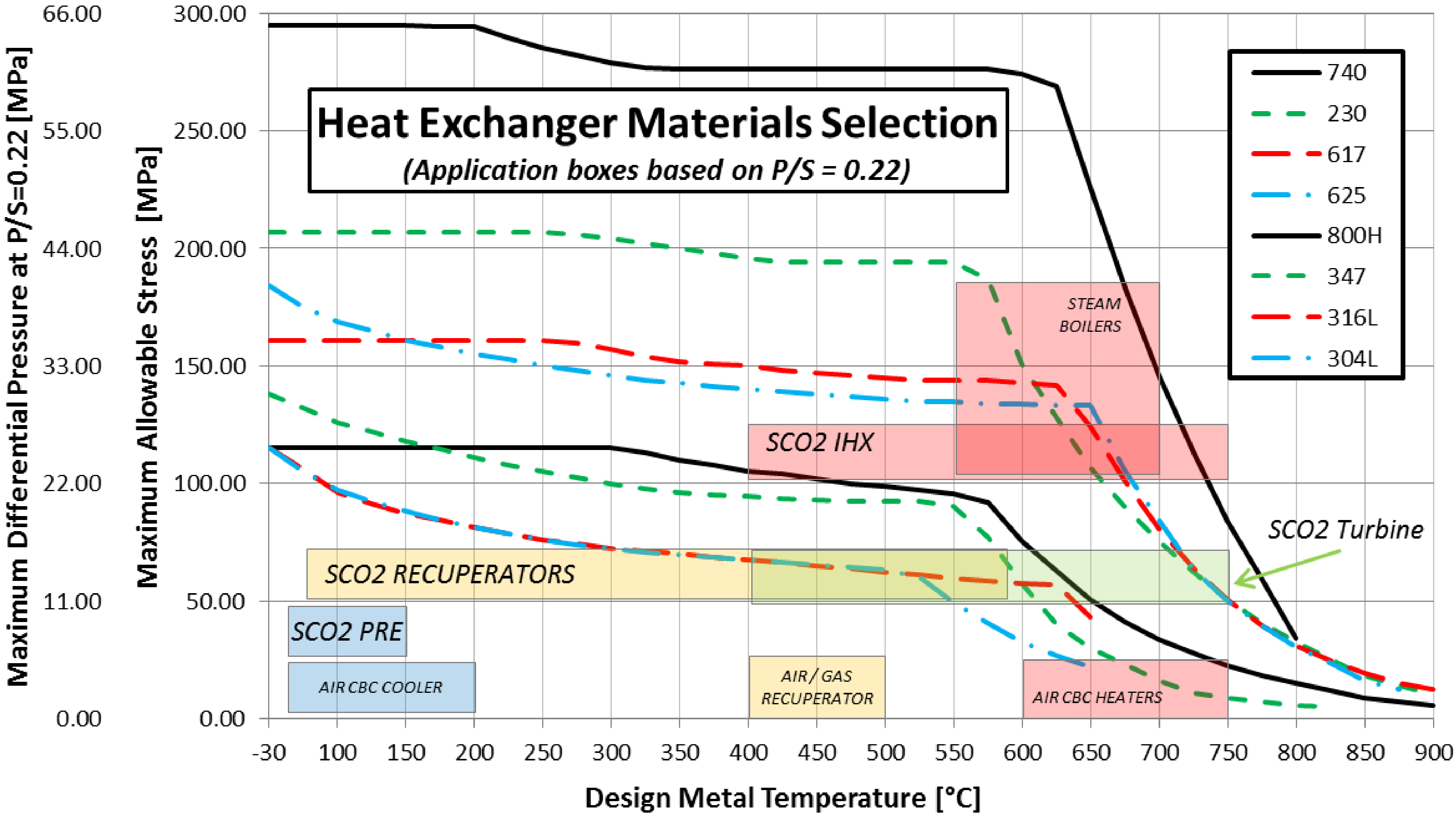
H. U. Frutschi, Closed-cycle gas turbines : operating experience and future potential. New York: ASME Press, 2005.

Scalable SCO2 CBC Systems



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.

Heat Exchanger Requirements



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)]

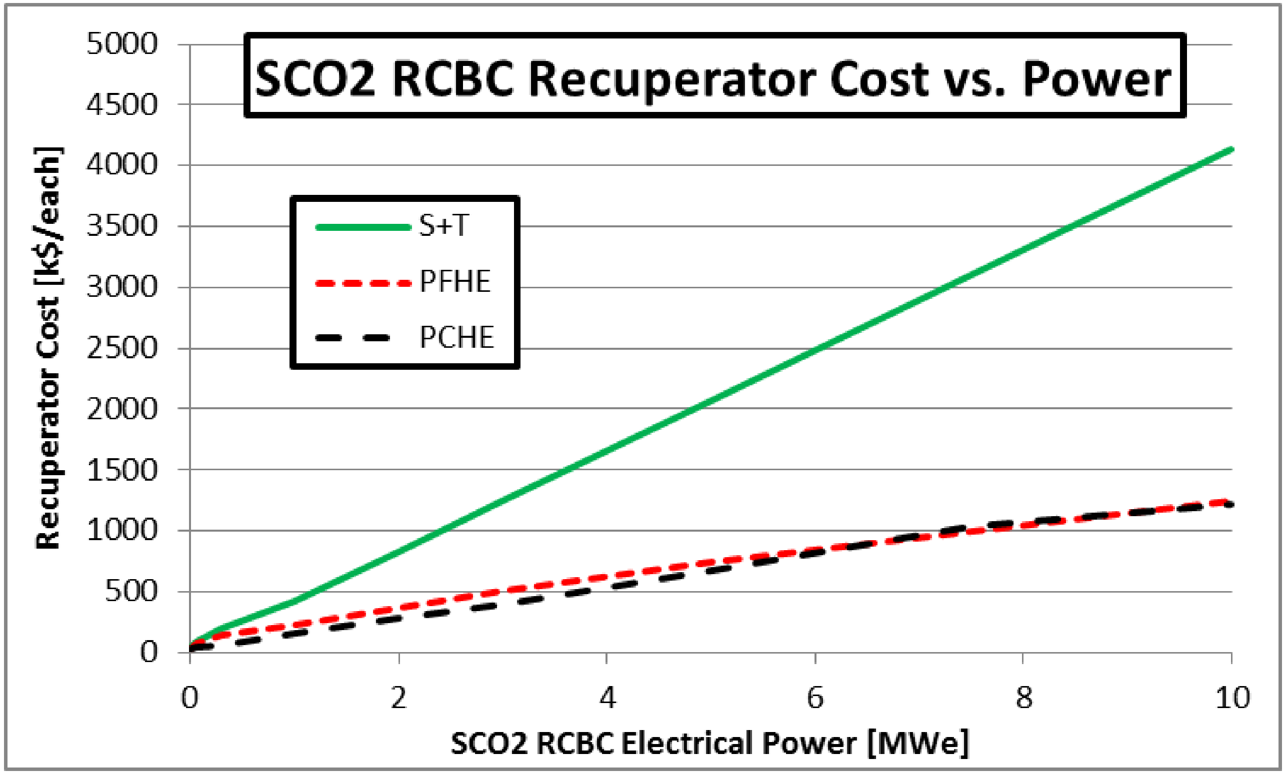
F_{mat} is a material cost factor

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.

DEVELOPMENTS FOR PCHES

The Printed Circuit Heat Exchanger

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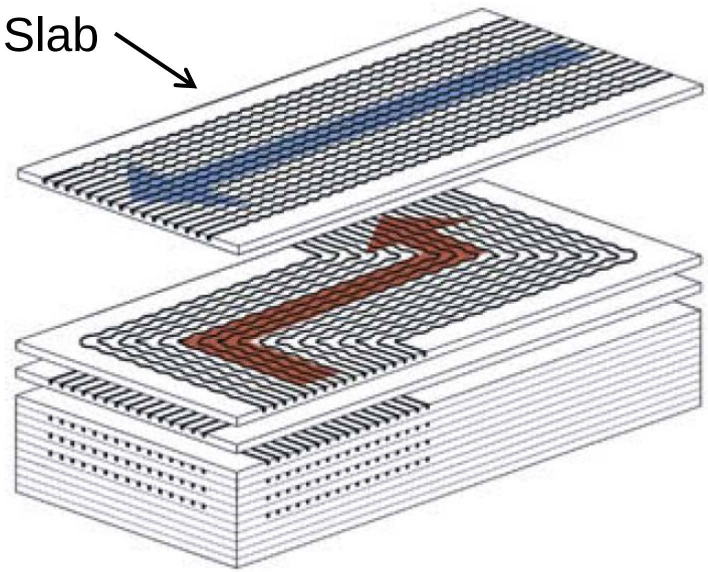
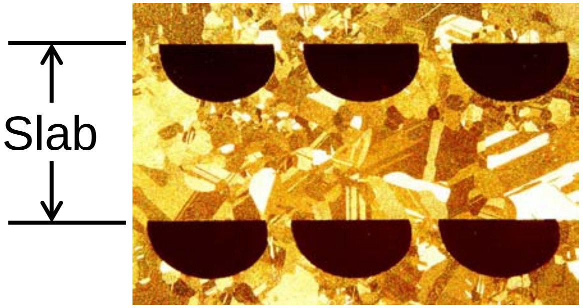
Heat Exchanger Core



Diffusion Bonding



Core and Manifold Assembly

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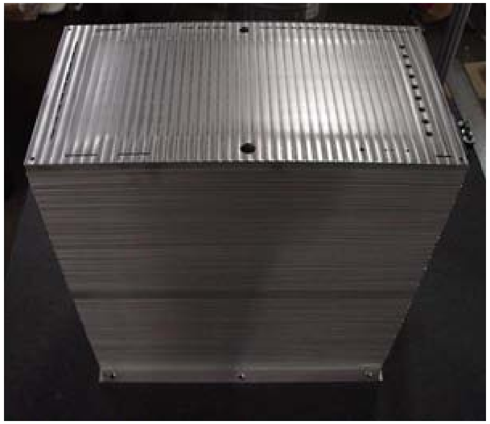
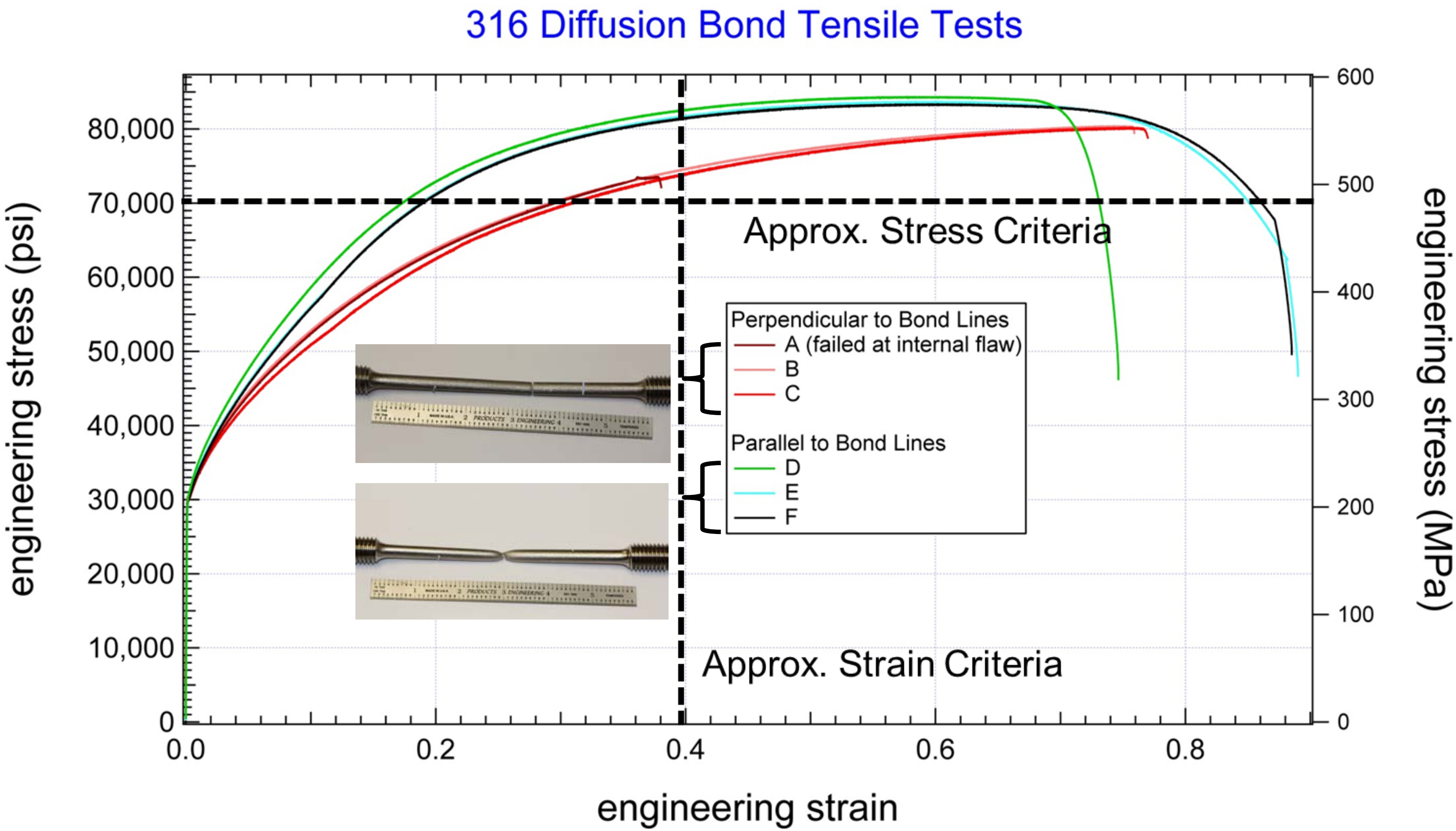
Partnership with VPE on PCHEs

Understand Near-Term Option

- Material and Bond Evaluation
  - Possible materials
  - Bonding defects
  - Develop U-stampable PCHEs
- PCHE Performance Testing
  - Pressure containment
  - Thermal-hydraulic testing
  - Thermal Fatigue testing
- Techno-Economic Optimization
  - Design -> Fabrication -> Testing

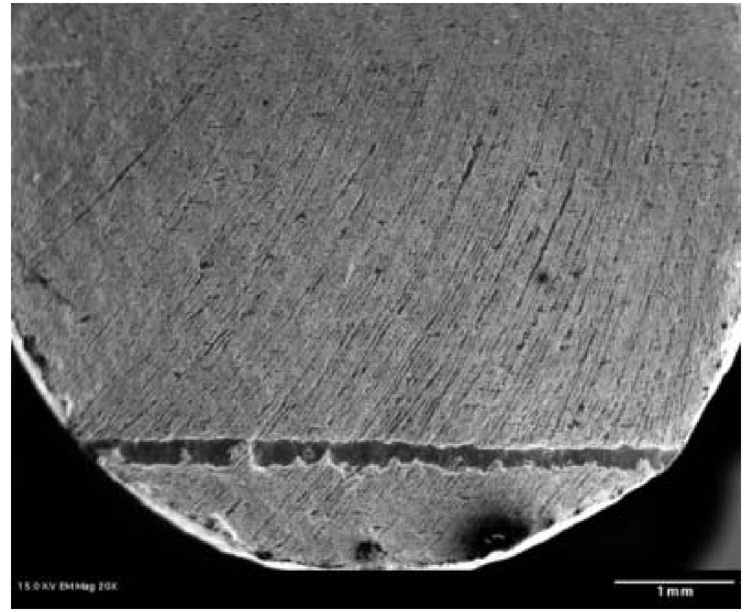


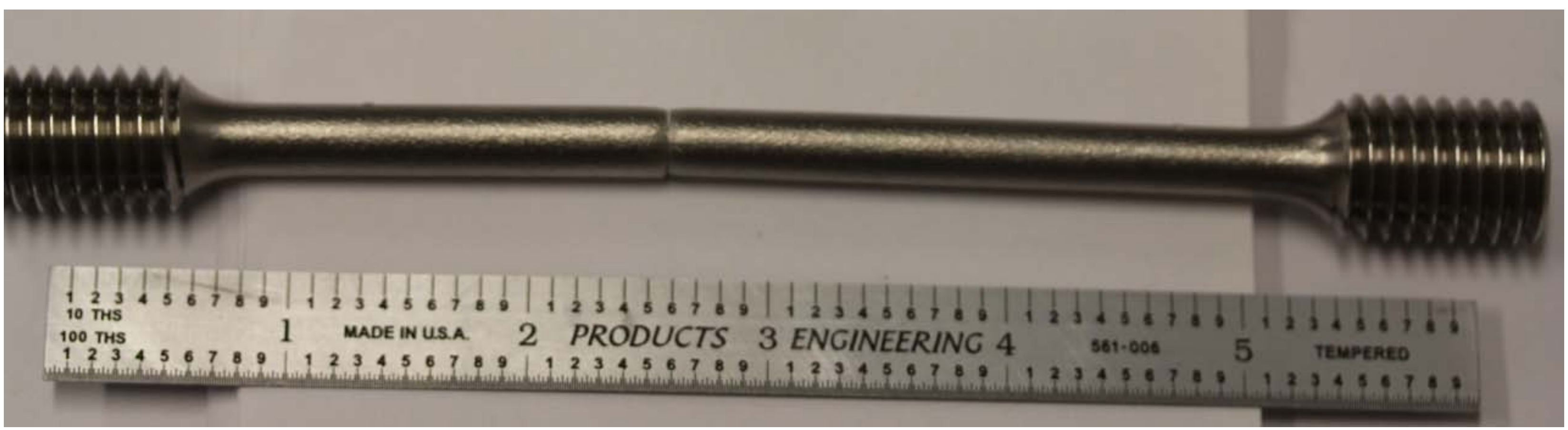
Review of 2014 Turbo Expo Results



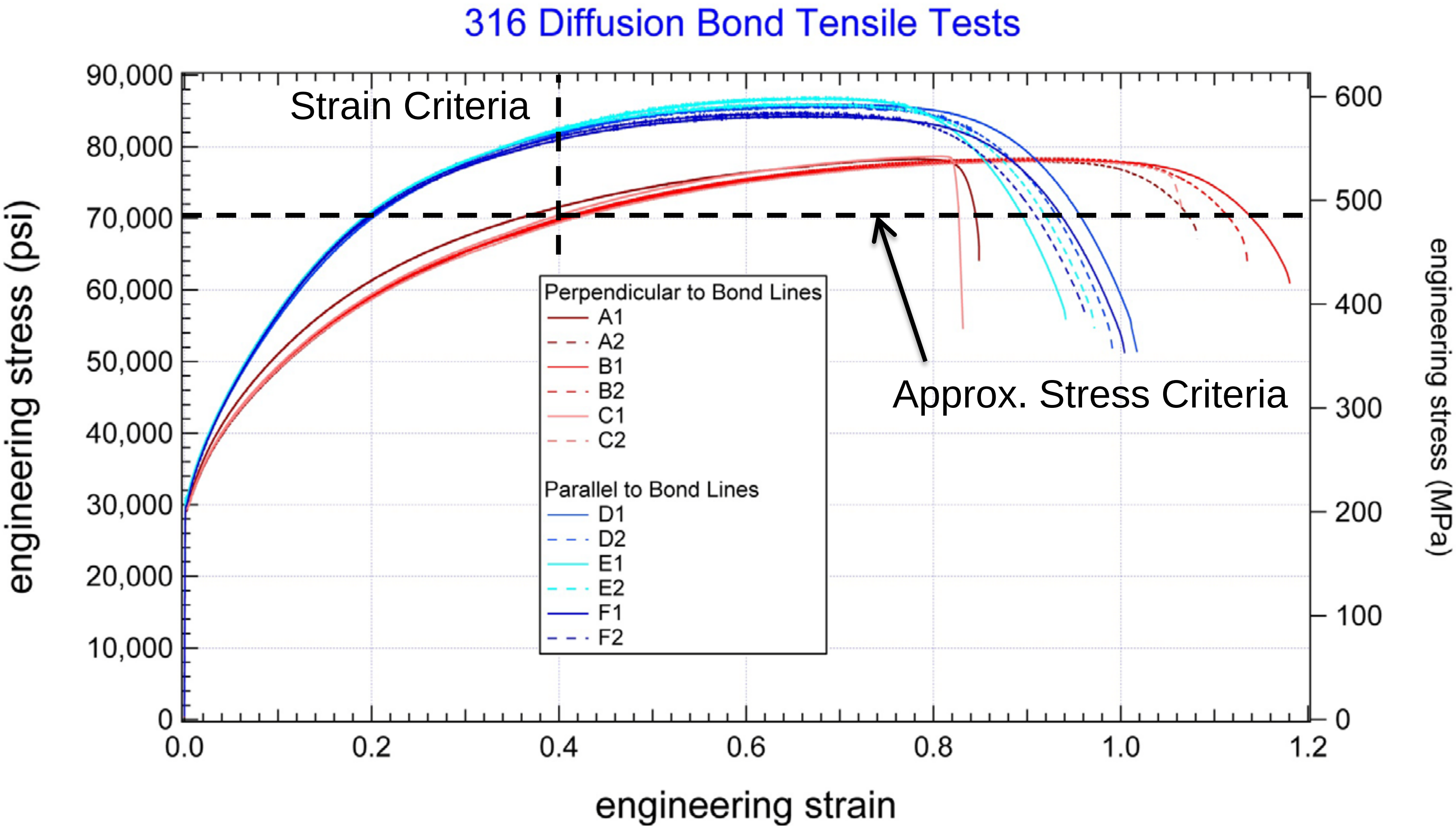
Analysis of the Failed Sample

- Likely due to visible trench
  - Matched on both surfaces
  - Foreign object inclusion (Carbonaceous material)
- Remedies in next blocks
  - Changed plate vendors
  - Tweaked bonding procedure

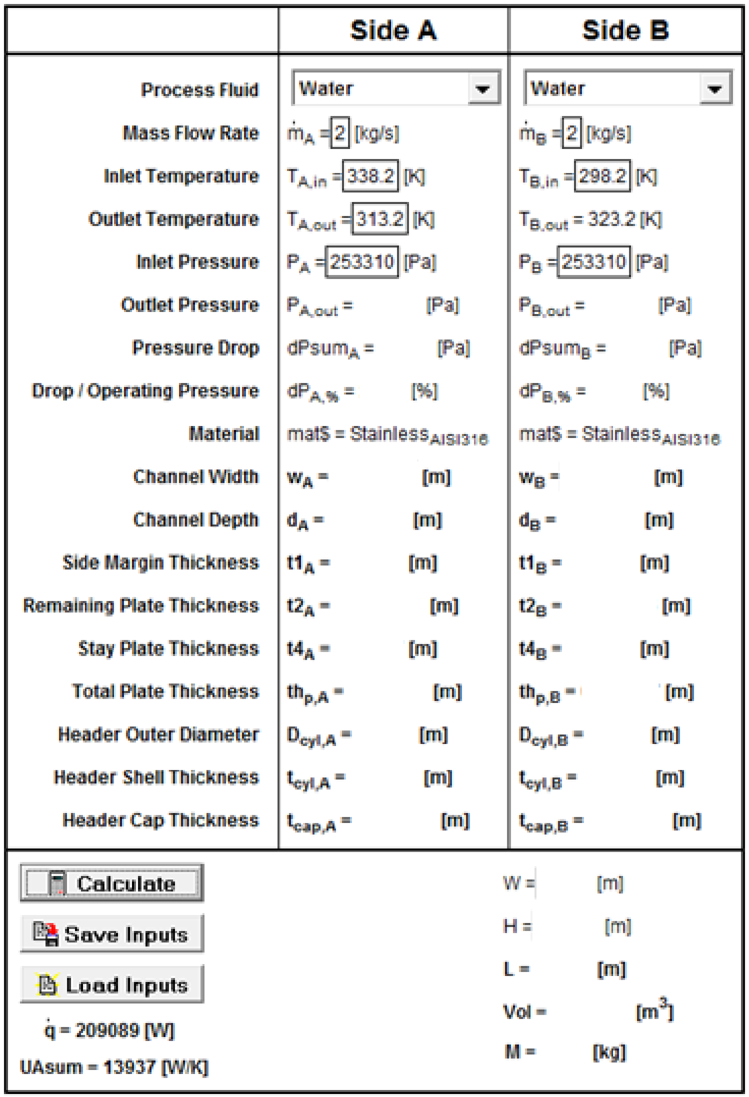


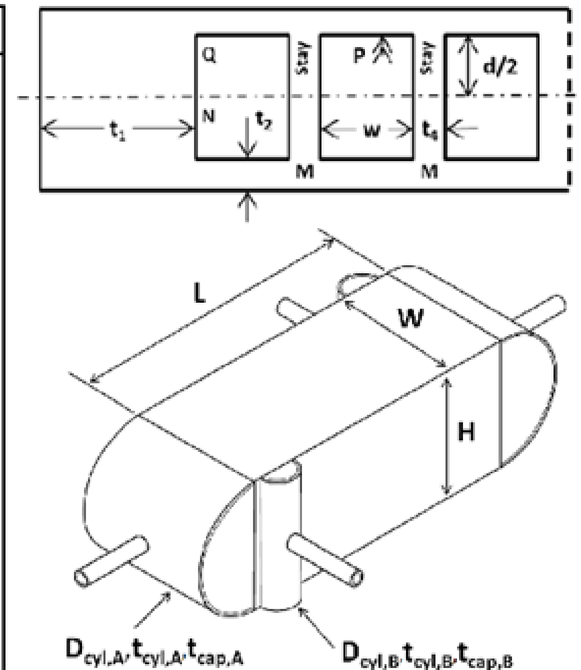


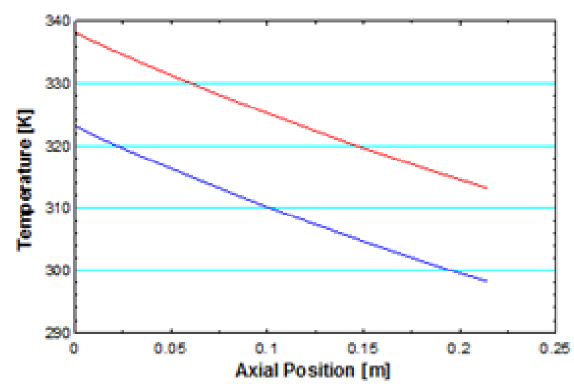
Two Sets of Satisfactory Samples



PCHE Design Software







DEVELOPMENTS FOR CAST METAL HEAT EXCHANGERS (CMHES)

SNL Cast Metal Heat Exchangers

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

Transitioning to Casting

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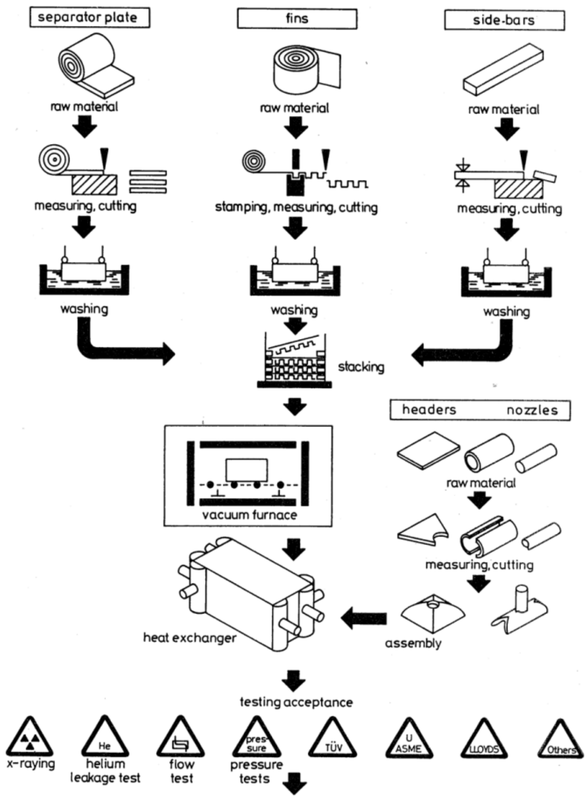

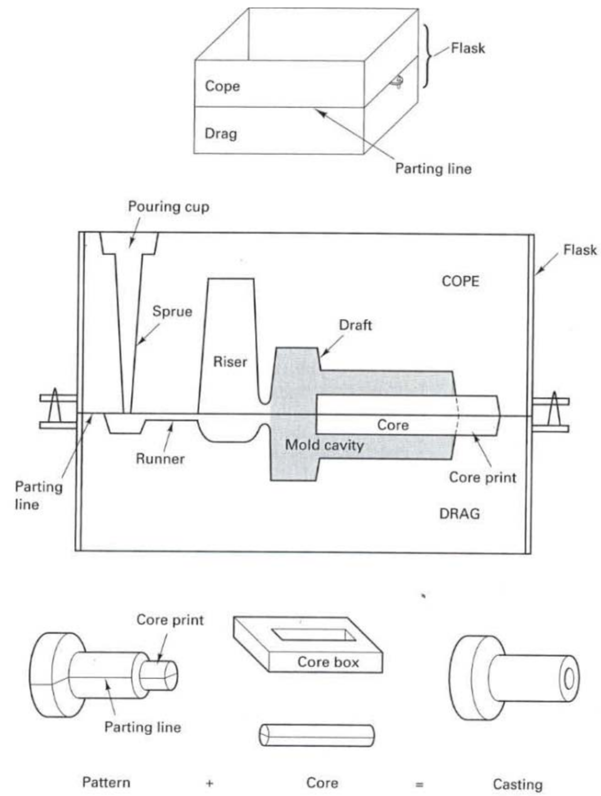

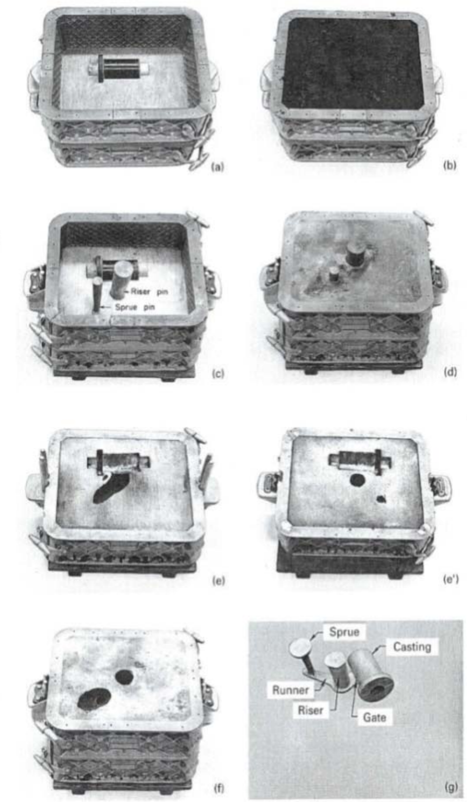

J. T. Black, R. A. Kohser, and E. P. DeGarmo, DeGarmo's materials and processes in manufacturing. Hoboken, NJ: Wiley, 2008.

CMHE Industrial Precedent

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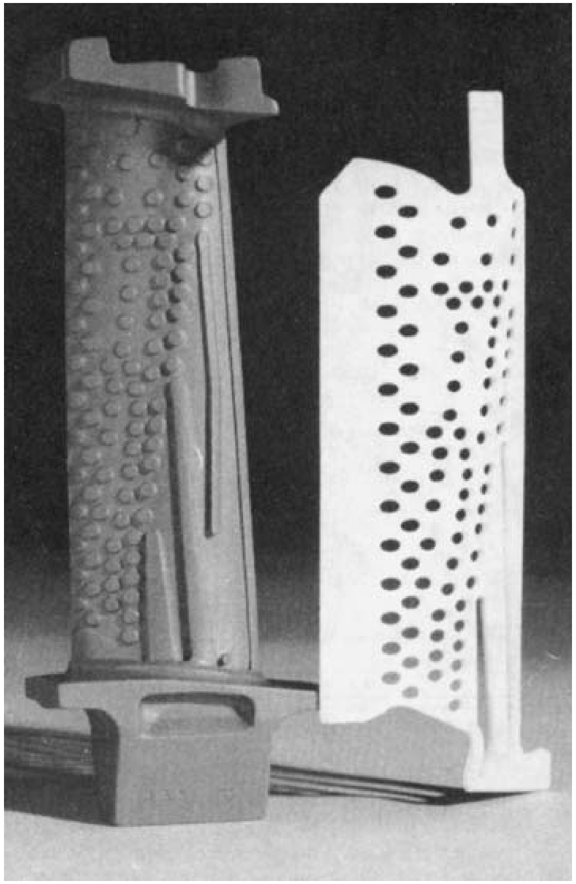
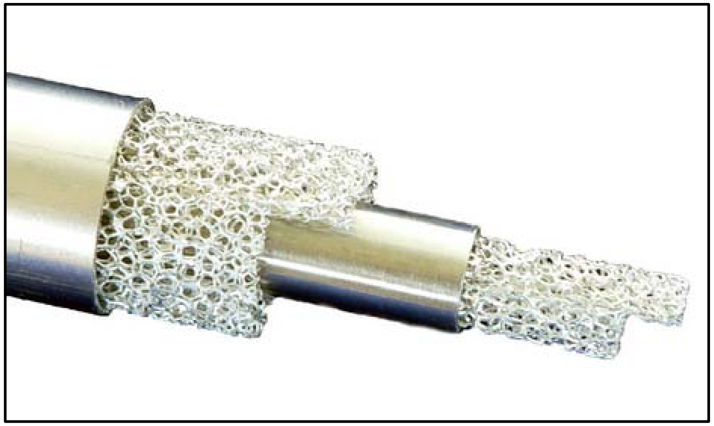
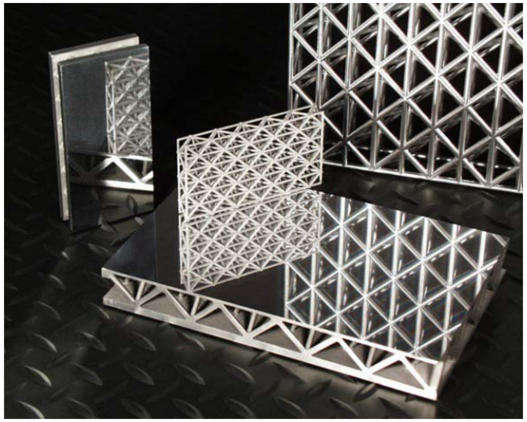
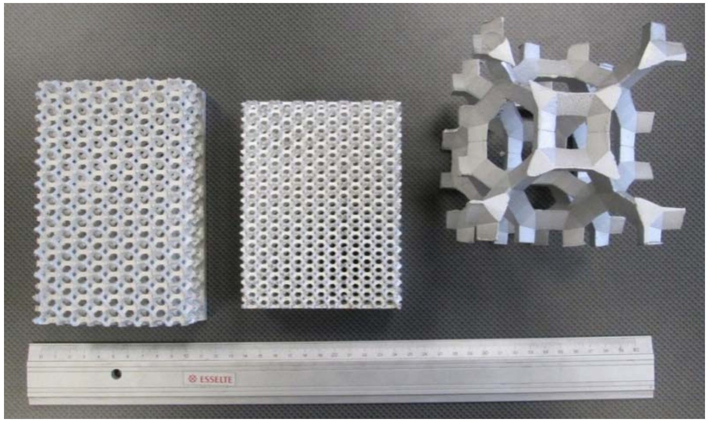


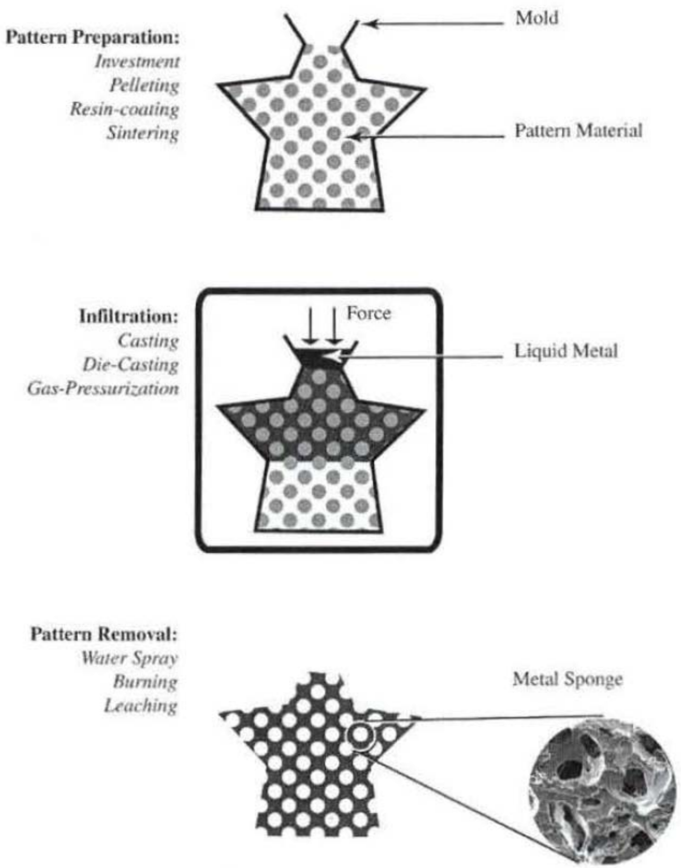


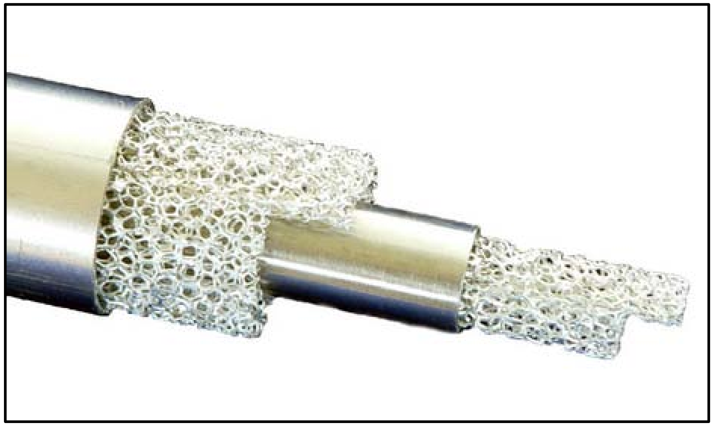


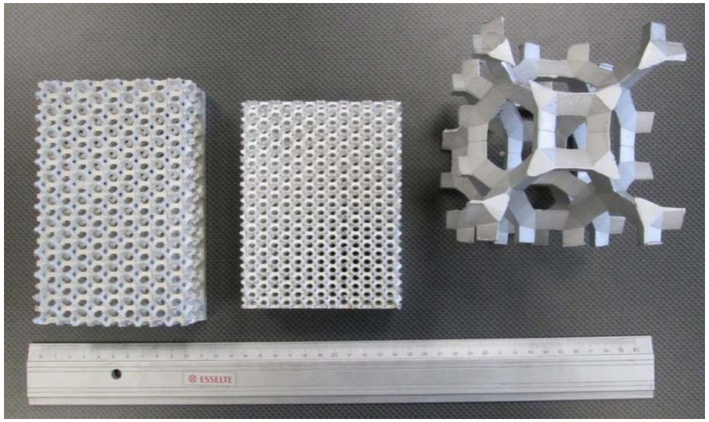


M. J. Donachie, Superalloys a technical guide. Materials Park, OH: ASM International, 2002.
http://www.fedtechgroup.com/advanced_materials/lbs/lbs_cast.html
http://www.ergaerospace.com/project-gallery.htm
http://www.alveotec.fr/nos-actualites/exemples-d-applications-mousses-metalliques_55.html

Industrial Precedent

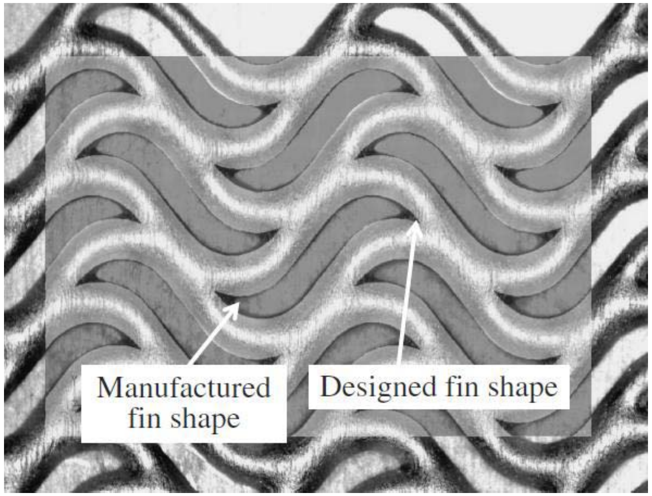


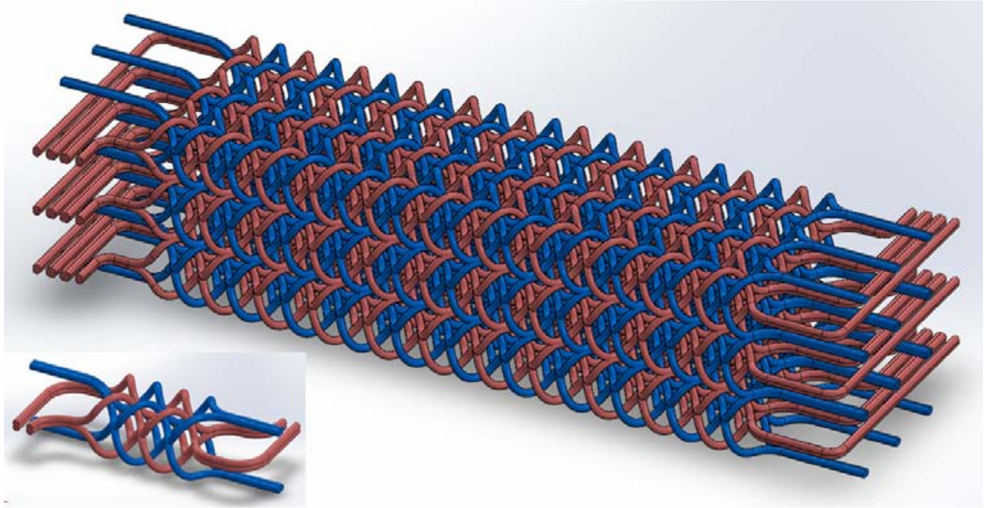


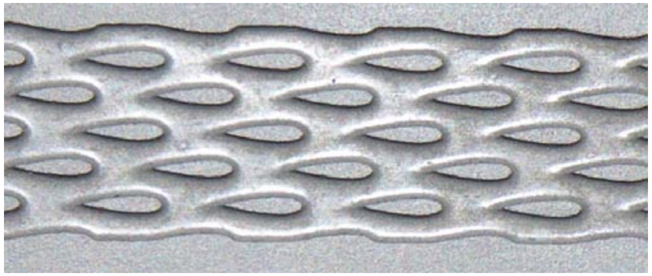


Handbook of Cellular Metals: Production, Processing, Applications. Weinheim: Wiley-VCH, 2002.

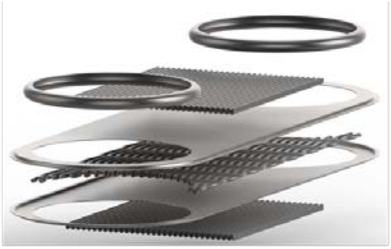
CMHE Recuperator Geometries





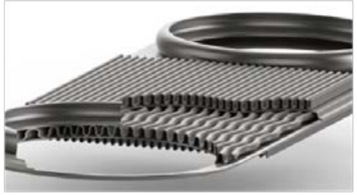


Brazed Plates



- Requires plate stamping

Cast Plates

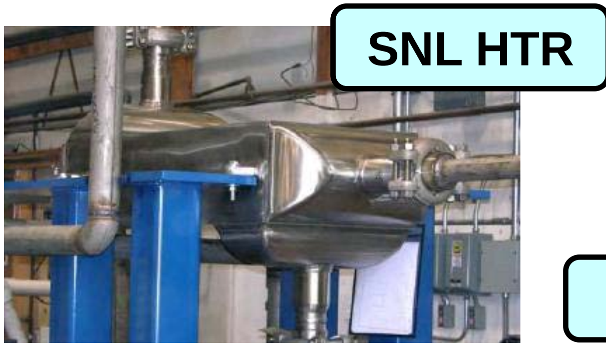


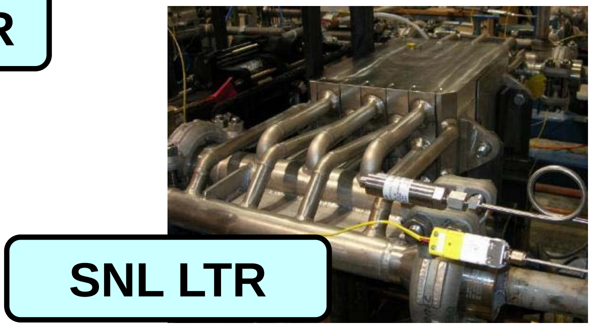
- Dry-fit multiple casting cores

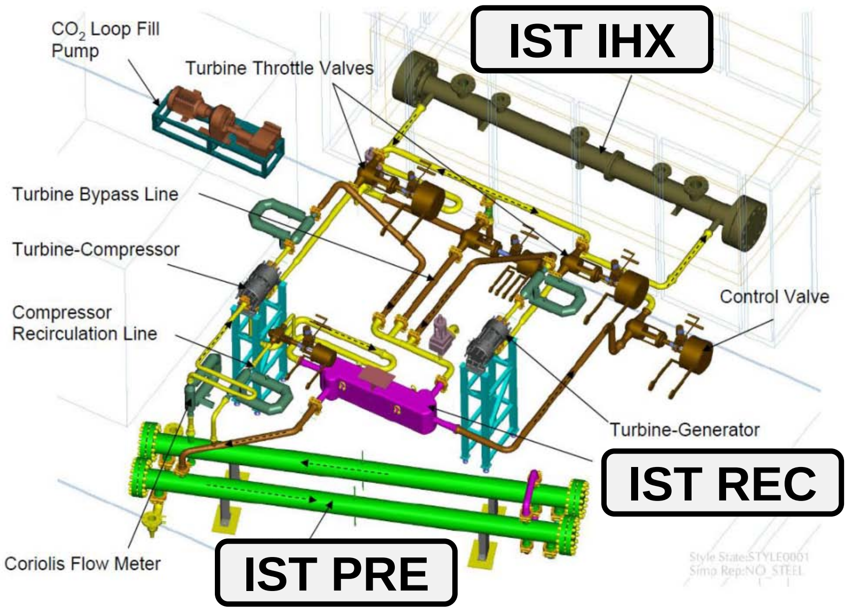
Unit-Cell Heat Exchanger

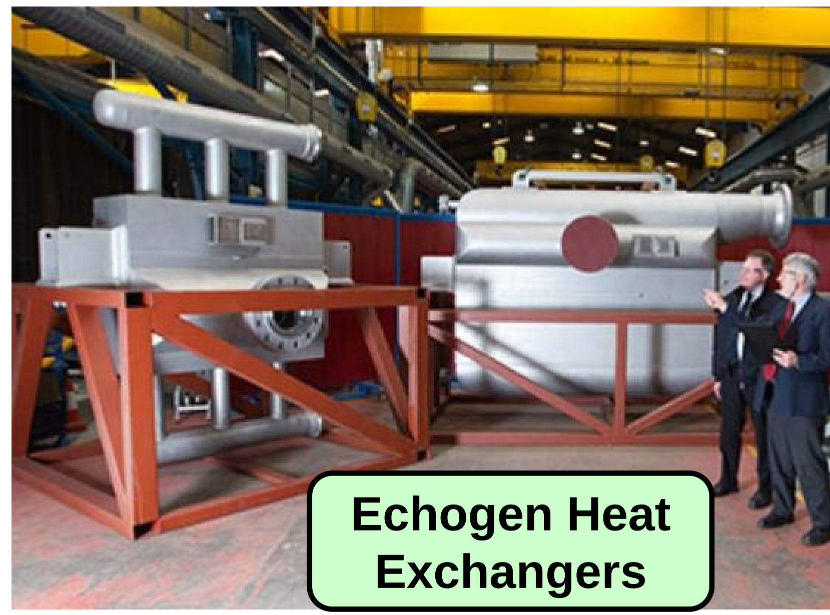
BACKUP SLIDES

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.

Commercial Unit Potential

Key Requirements:
- ✓ High Pressure
- ✓ High Temperature
- ✓ Corrosion Resistant
- ✓ High Reliability
- ✓ Compact Geometry
- ✓ Scalable to 150 MWe

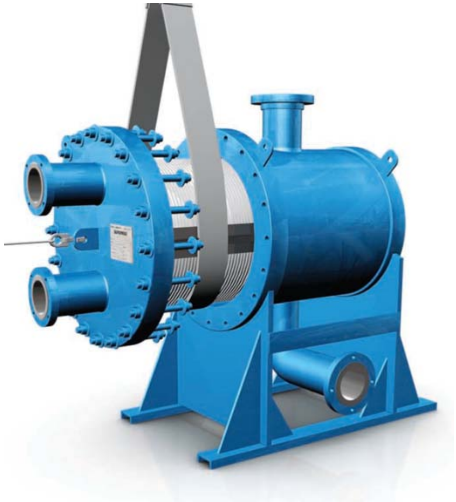
$$\beta = \frac{A_s}{V} = \frac{4\phi}{d_h}$$

Coil-Wound
10 to 300 [m²/m³]

Shell and Tube
10 to 200 [m²/m³]

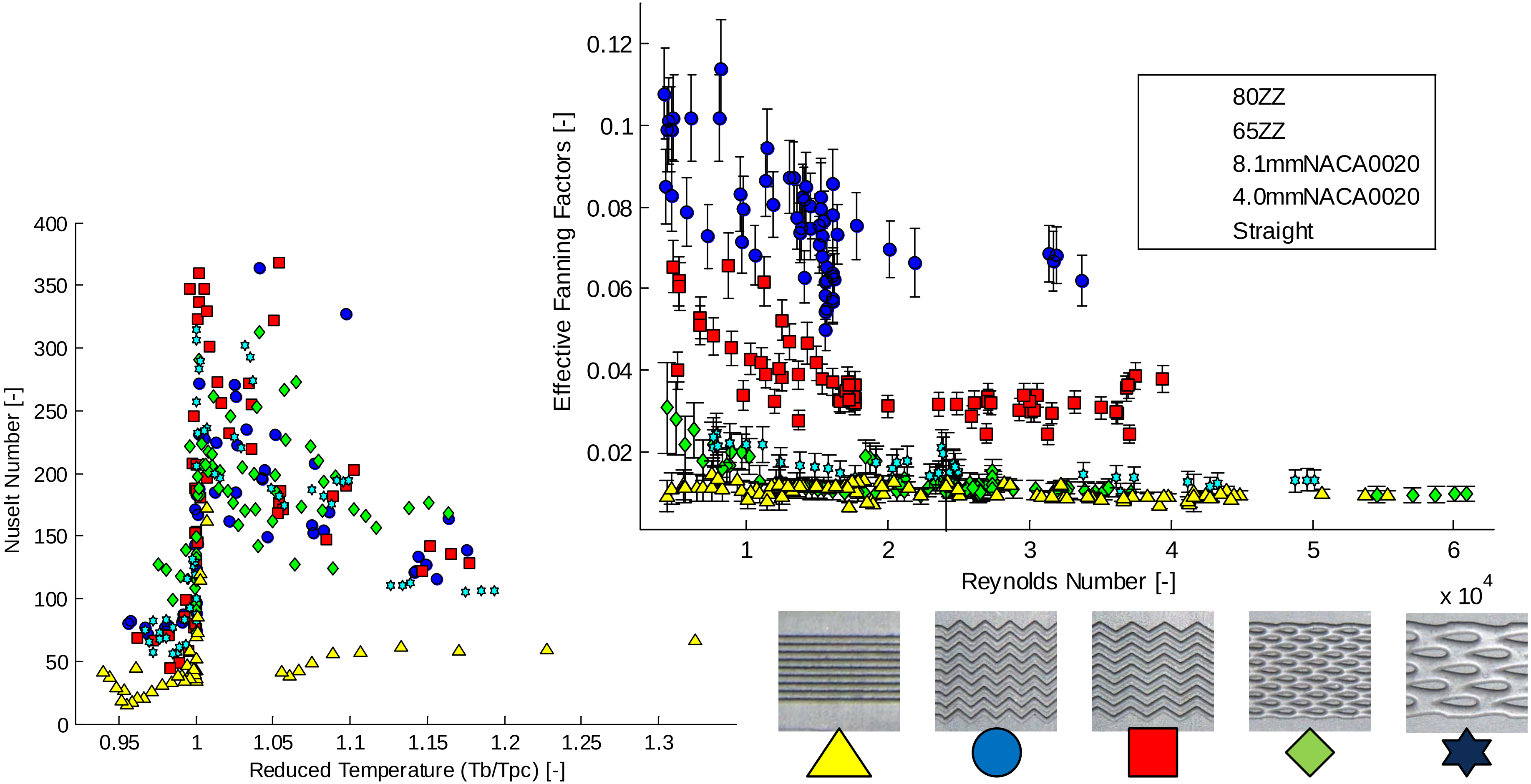
Plate-Fin
200 to 800 [m²/m³]

Printed Circuit
200 to 5000 [m²/m³]



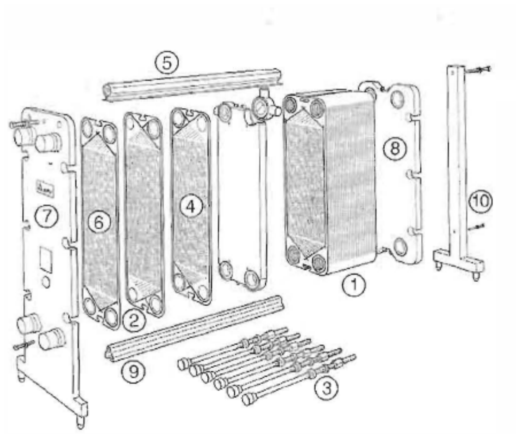
Shell and Plate
100 to 600 [m²/m³]

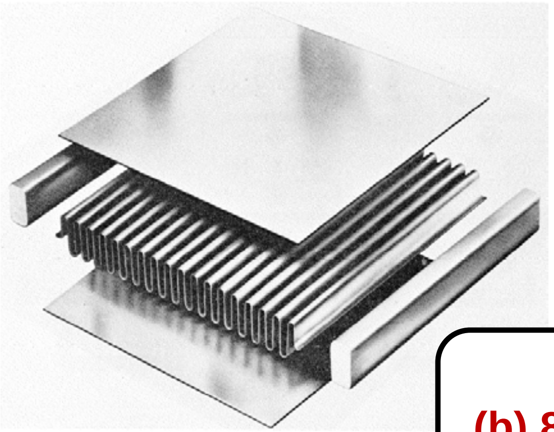
PCHE Thermal-Hydraulic Performance



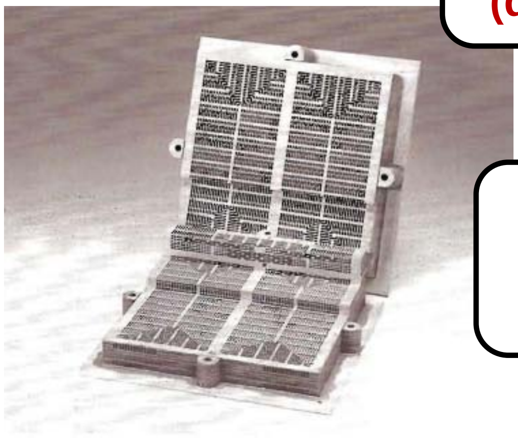
Carlson, M. (2012). *Measurement and Analysis of the Thermal and Hydraulic Performance of Several Printed Circuit Heat Exchanger Channel Geometries* (Master of Science). University of Wisconsin - Madison, Madison, WI.

PHE
120 to 660





PFHE
(b) 800 to 1500
(d) 700 to 800



CBHE
(Marbond)
Up to 10000

PCHE
(d) 200 to 5000

HEAT EXCHANGER COMPACTNESS

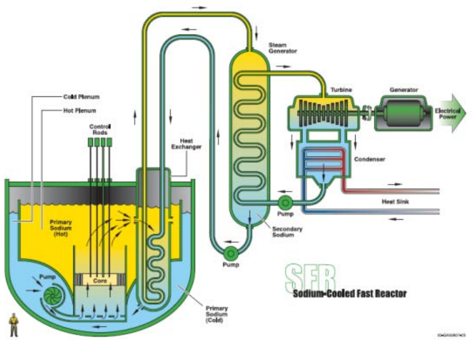
Surface Area Density: $\beta = \frac{A_s}{V} = \frac{4\phi}{d_h}$

Potential Applications

Coal / Nuclear
Steam Rankine

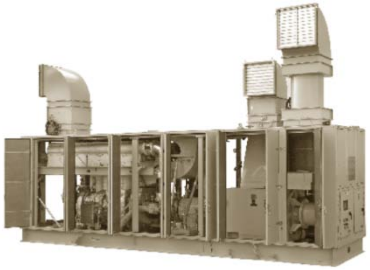
MARINE
Rolls-Royce WR-21
Type 45 Destroyer

VEHICULAR
Honeywell AGT1500
M1 Abrams Tank



GenIV Nuclear
Sodium Fast Reactor

Refrigeration
Commercial, Cryogenic



STATIONARY
Solar Turbines
Mercury 50