Exceptional service in the national interest

Sandia National Laboratories

The SEARCH Software Suite
Code Capabilities and Experimental Comparison

The 5th International Symposium - Supercritical CO2 Power Cycles

March 28-31, 2016, San Antonio, Texas, USA

*Carlson, M. D, Bell, C., Schalansky, C., Fleming, D. F., Rochau, G.

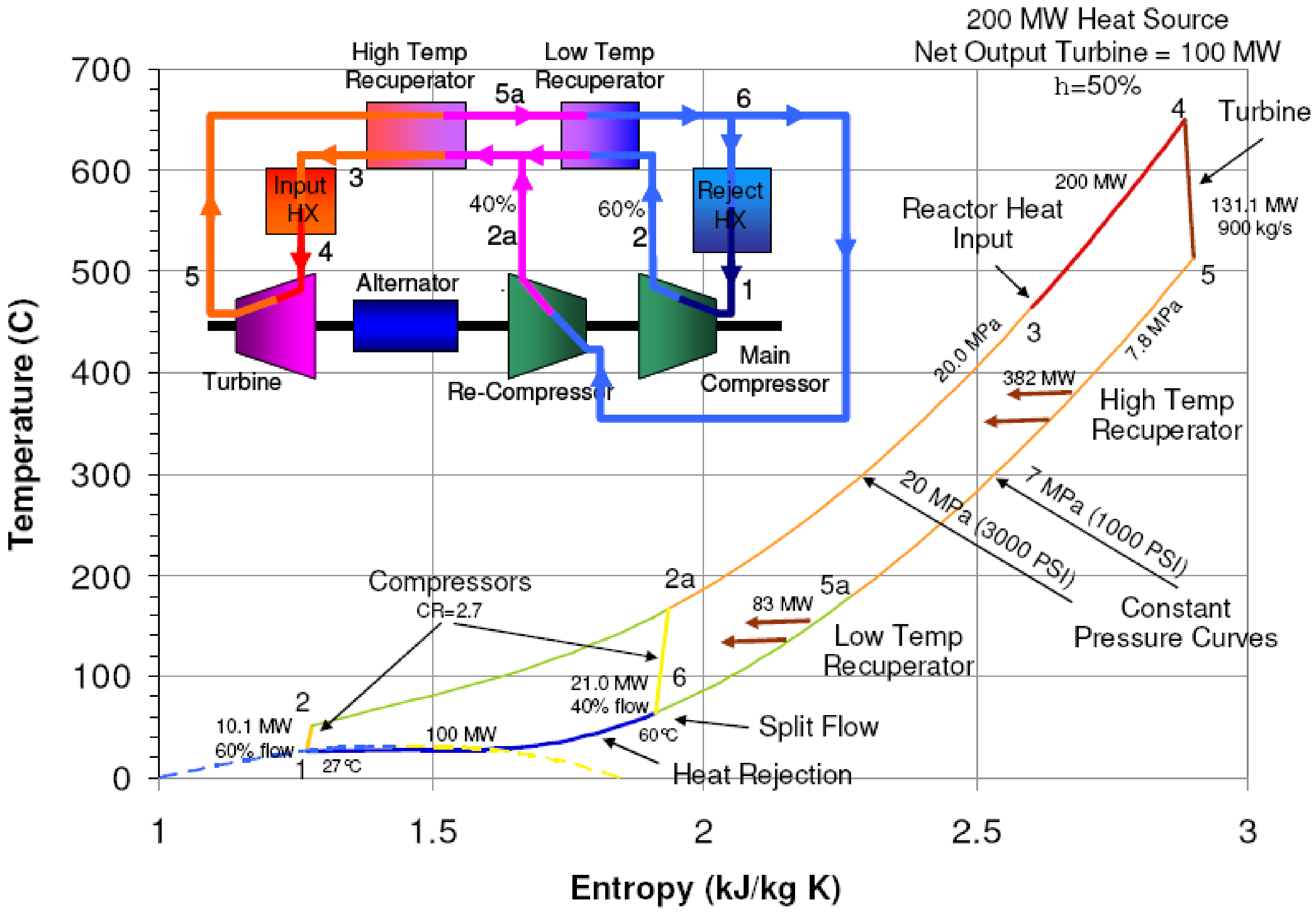
U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

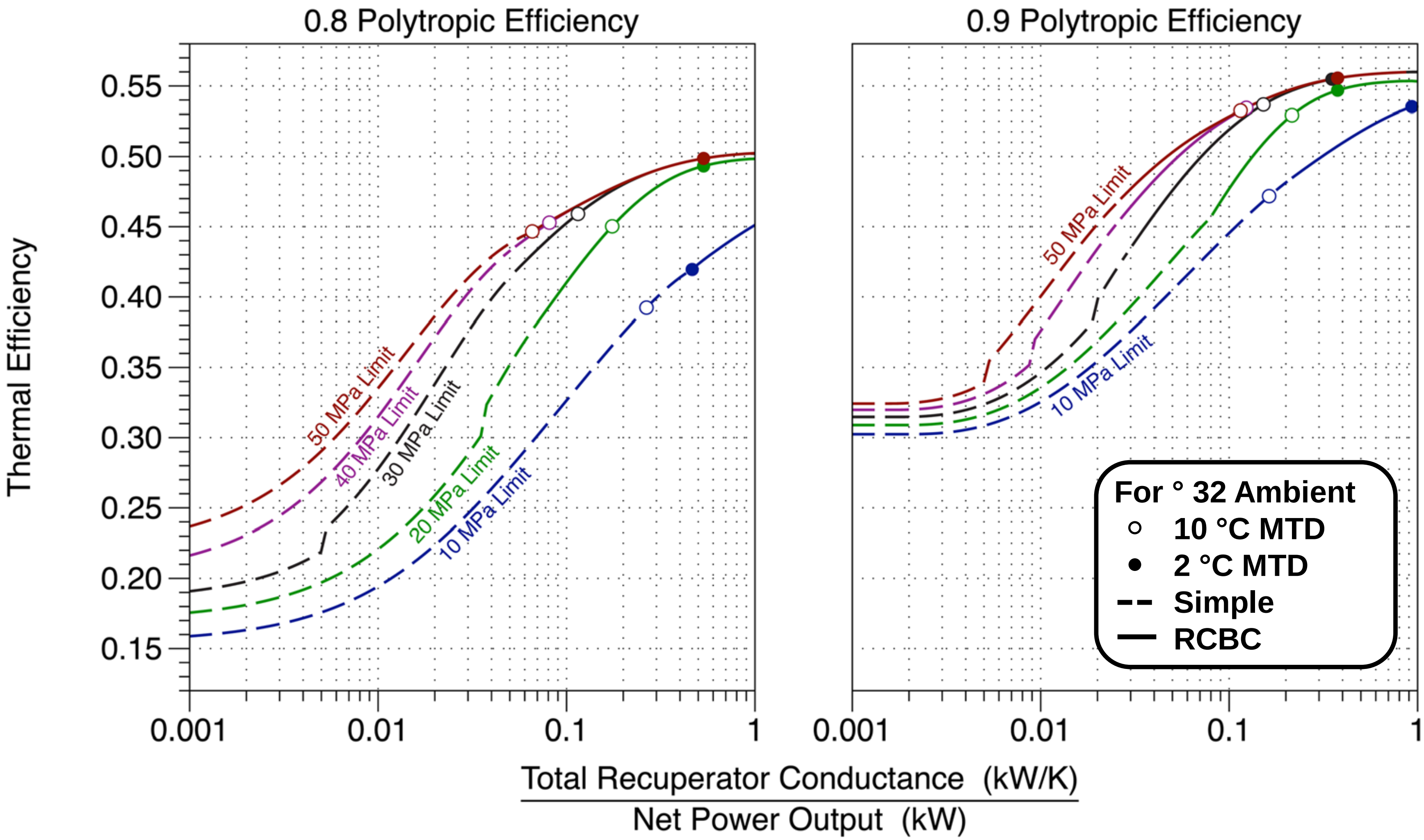
BACKGROUND

Supercritical CO_2 Brayton Cycle



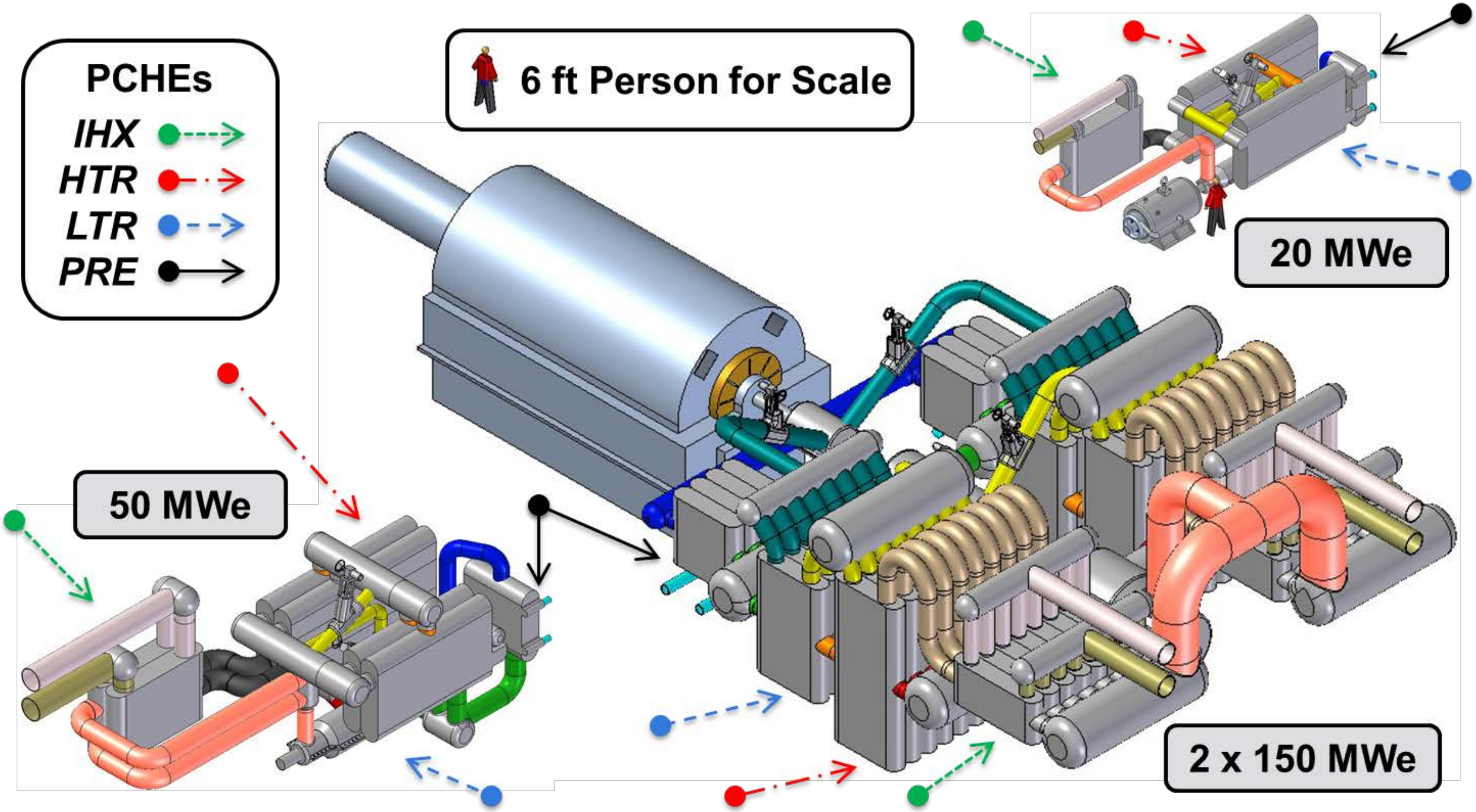
E. J. Parma, S. A. Wright, M. E. Vernon, D. D. Fleming, G. E. Rochau, A. J. Suo-Anttila, A. Al Rashdan, and P. V. Tsvetkov, “Supercritical CO2 Direct Cycle Gas Fast Reactor (SC-GFR) Concept,” Sandia National Laboratories, Albuquerque, NM, USA, SAND 2011-2525, May 2011.

sCO2 Brayton Cycles Recuperation



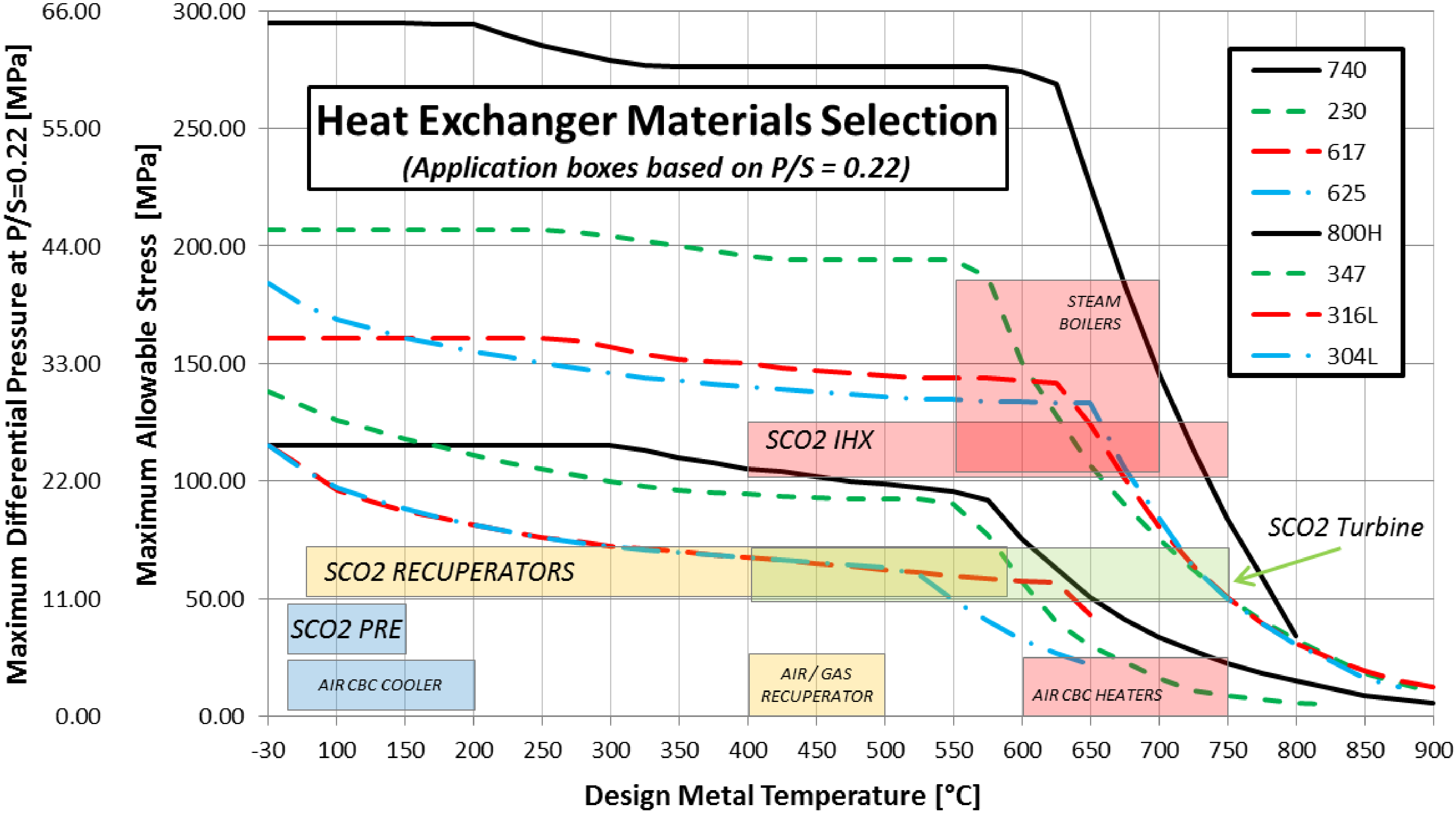
J. Dyreby, S. Klein, G. Nellis, and D. Reindl, “Design Considerations for Supercritical Carbon Dioxide Brayton Cycles With Recompression,” *Journal of Engineering for Gas Turbines and Power*, vol. 136, no. 10, p. 101701, Jul. 2014.

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)]

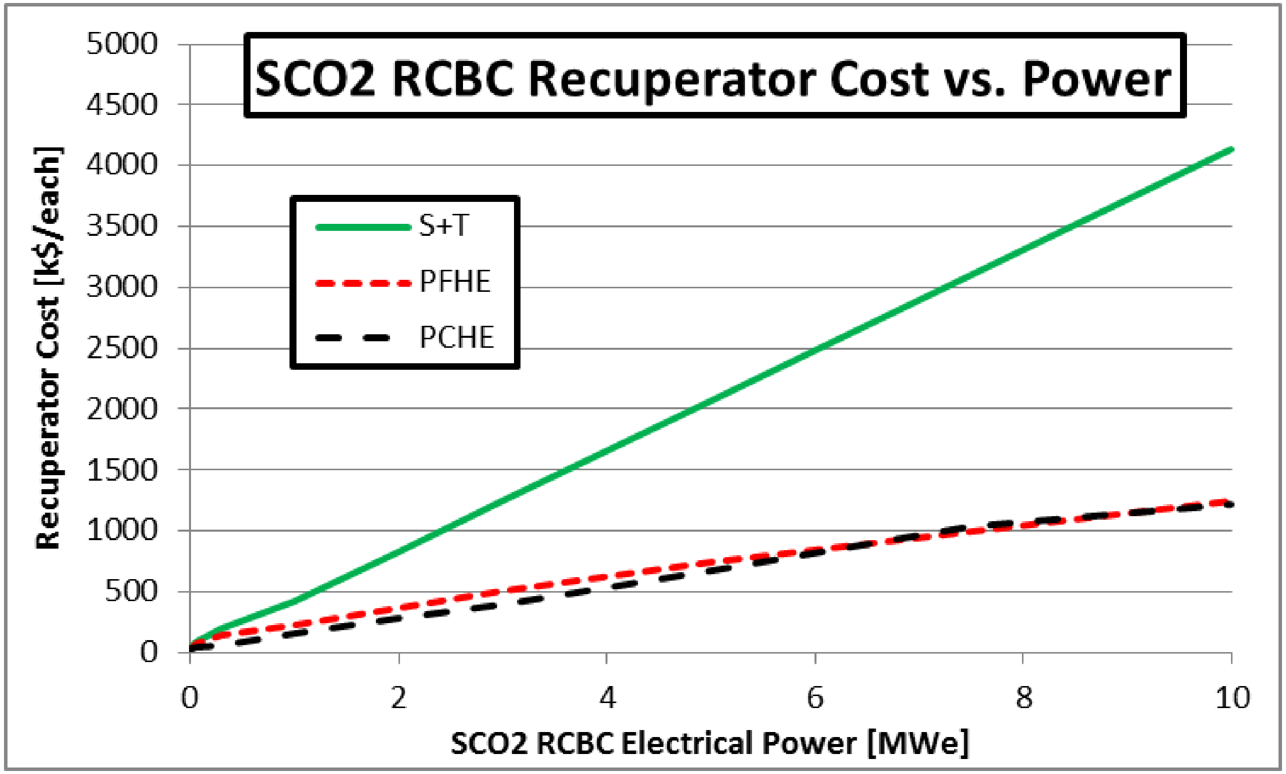
F_{mat} is a material cost factor

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]

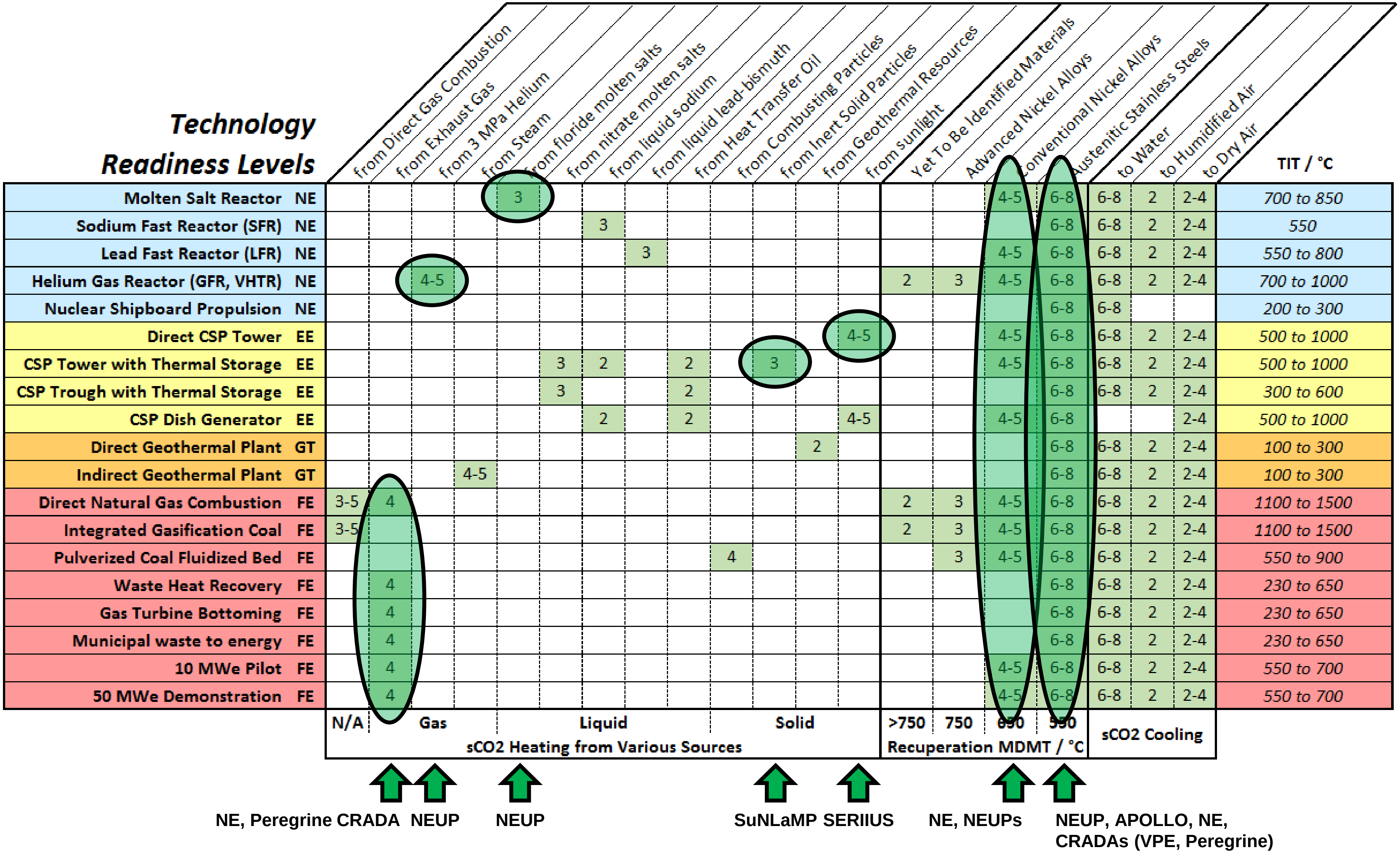


ESDU, "Selection and Costing of Heat Exchangers," Engineering Sciences Data Unit, ESDU 92013, Dec. 1994.

Heat Exchanger Development Gaps

Technology Readiness Levels		from Direct Gas Combustion	from Exhaust Gas	from 3 MPa Helium	from Steam	from floride molten salts	from nitrate molten salts	from liquid sodium	from liquid lead-bismuth	from Heat Transfer Oil	from Combusting Particles	from Inert Solid Particles	from Geothermal Resources	from sunlight	Yet To Be Identified Materials	Advanced Nickel Alloys	Conventional Nickel Alloys	Austenitic Stainless Steels	to Water	to Humidified Air	to Dry Air	**TIT / °C**
Molten Salt Reactor	**NE**					3											4-5	6-8	6-8	2	2-4	*700 to 850*
Sodium Fast Reactor (SFR)	**NE**							3										6-8	6-8	2	2-4	*550*
Lead Fast Reactor (LFR)	**NE**								3								4-5	6-8	6-8	2	2-4	*550 to 800*
Helium Gas Reactor (GFR, VHTR)	**NE**			4-5											2	3	4-5	6-8	6-8	2	2-4	*700 to 1000*
Nuclear Shipboard Propulsion	**NE**																	6-8	6-8			*200 to 300*
Direct CSP Tower	**EE**													4-5			4-5	6-8	6-8	2	2-4	*500 to 1000*
CSP Tower with Thermal Storage	**EE**						3	2		2		3					4-5	6-8	6-8	2	2-4	*500 to 1000*
CSP Trough with Thermal Storage	**EE**						3			2								6-8	6-8	2	2-4	*300 to 600*
CSP Dish Generator	**EE**							2		2				4-5			4-5	6-8			2-4	*500 to 1000*
Direct Geothermal Plant	**GT**												2					6-8	6-8	2	2-4	*100 to 300*
Indirect Geothermal Plant	**GT**				4-5													6-8	6-8	2	2-4	*100 to 300*
Direct Natural Gas Combustion	**FE**	3-5	4												2	3	4-5	6-8	6-8	2	2-4	*1100 to 1500*
Integrated Gasification Coal	**FE**	3-5													2	3	4-5	6-8	6-8	2	2-4	*1100 to 1500*
Pulverized Coal Fluidized Bed	**FE**										4					3	4-5	6-8	6-8	2	2-4	*550 to 900*
Waste Heat Recovery	**FE**		4															6-8	6-8	2	2-4	*230 to 650*
Gas Turbine Bottoming	**FE**		4															6-8	6-8	2	2-4	*230 to 650*
Municipal waste to energy	**FE**		4															6-8	6-8	2	2-4	*230 to 650*
10 MWe Pilot	**FE**		4														4-5	6-8	6-8	2	2-4	*550 to 700*
50 MWe Demonstration	**FE**		4														4-5	6-8	6-8	2	2-4	*550 to 700*
		N/A	**Gas**			**Liquid**					**Solid**				**>750**	**750**	**650**	**550**	**sCO2 Cooling**			
		sCO2 Heating from Various Sources													**Recuperation MDMT / °C**							

Development Gaps Addressed



Technology Readiness Levels		from Direct Gas Combustion	from Exhaust Gas	from 3 MPa Helium	from Steam	from floride molten salts	from nitrate molten salts	from liquid sodium	from liquid lead-bismuth	from Heat Transfer Oil	from Combusting Particles	from Inert Solid Particles	from Geothermal Resources	from sunlight	Yet To Be Identified Materials	Advanced Nickel Alloys	Conventional Nickel Alloys	Austenitic Stainless Steels	to Water	to Humidified Air	to Dry Air	TIT / °C
Molten Salt Reactor	NE					3											4-5	6-8	6-8	2	2-4	700 to 850
Sodium Fast Reactor (SFR)	NE							3										6-8	6-8	2	2-4	550
Lead Fast Reactor (LFR)	NE								3								4-5	6-8	6-8	2	2-4	550 to 800
Helium Gas Reactor (GFR, VHTR)	NE			4-5											2	3	4-5	6-8	6-8	2	2-4	700 to 1000
Nuclear Shipboard Propulsion	NE																	6-8	6-8			200 to 300
Direct CSP Tower	EE													4-5			4-5	6-8	6-8	2	2-4	500 to 1000
CSP Tower with Thermal Storage	EE						3	2		2		3					4-5	6-8	6-8	2	2-4	500 to 1000
CSP Trough with Thermal Storage	EE						3			2								6-8	6-8	2	2-4	300 to 600
CSP Dish Generator	EE							2		2				4-5			4-5	6-8			2-4	500 to 1000
Direct Geothermal Plant	GT												2					6-8	6-8	2	2-4	100 to 300
Indirect Geothermal Plant	GT				4-5													6-8	6-8	2	2-4	100 to 300
Direct Natural Gas Combustion	FE	3-5	4												2	3	4-5	6-8	6-8	2	2-4	1100 to 1500
Integrated Gasification Coal	FE	3-5													2	3	4-5	6-8	6-8	2	2-4	1100 to 1500
Pulverized Coal Fluidized Bed	FE										4					3	4-5	6-8	6-8	2	2-4	550 to 900
Waste Heat Recovery	FE		4															6-8	6-8	2	2-4	230 to 650
Gas Turbine Bottoming	FE		4															6-8	6-8	2	2-4	230 to 650
Municipal waste to energy	FE		4															6-8	6-8	2	2-4	230 to 650
10 MWe Pilot	FE		4														4-5	6-8	6-8	2	2-4	550 to 700
50 MWe Demonstration	FE		4														4-5	6-8	6-8	2	2-4	550 to 700
		N/A	Gas			Liquid					Solid				>750	750	650	550	sCO2 Cooling			
		sCO2 Heating from Various Sources													Recuperation MDMT / °C							

NE, Peregrine CRADA

NEUP

NEUP

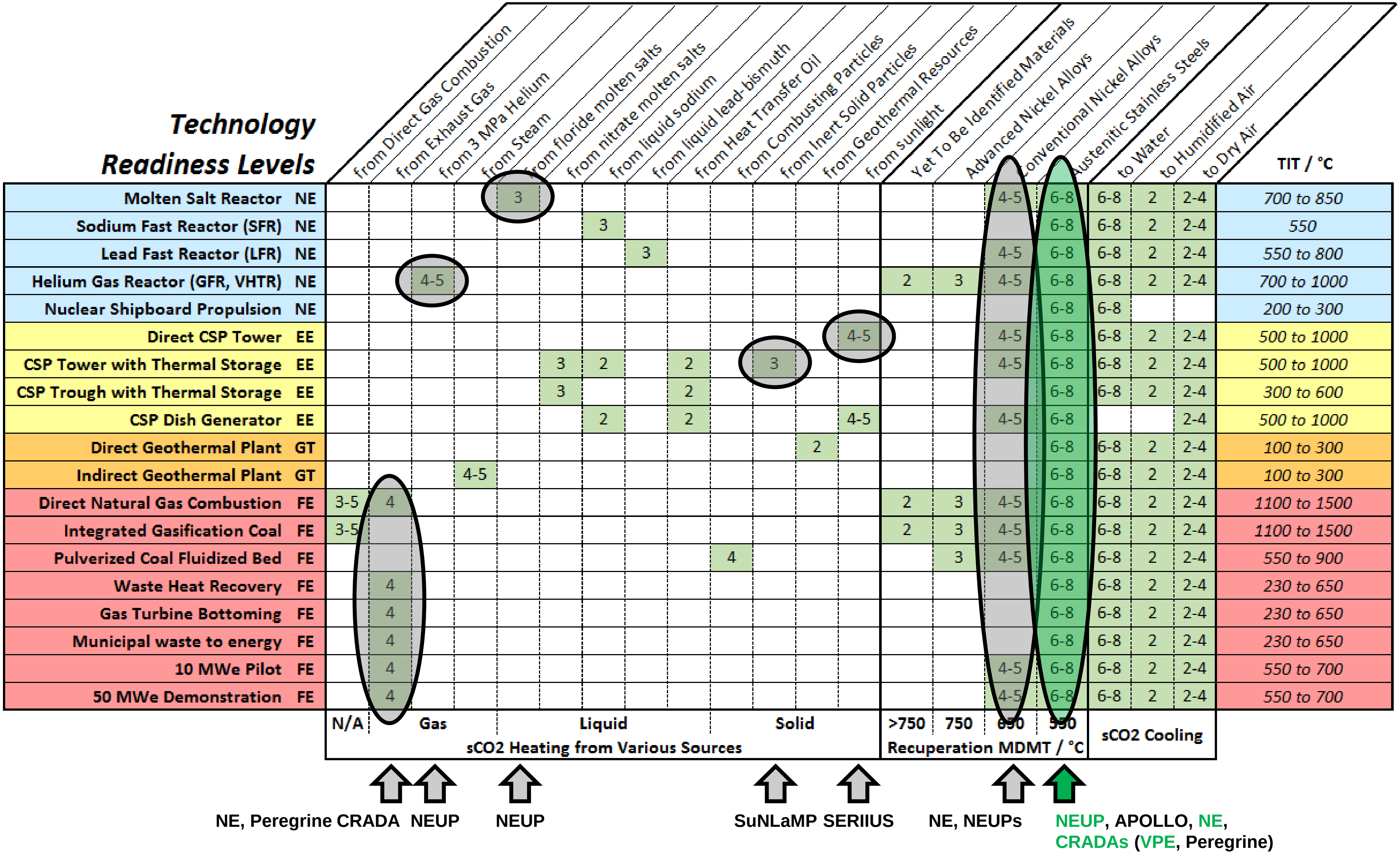
SuNLaMP

SERIIUS

NE, NEUPs

NEUP, APOLLO, NE, CRADAs (VPE, Peregrine)

Development Gaps Addressed



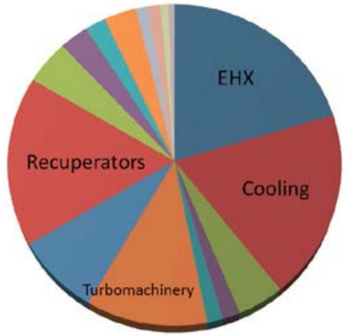
Technology Readiness Levels		from Direct Gas Combustion	from Exhaust Gas	from 3 MPa Helium	from Steam	from floride molten salts	from nitrate molten salts	from liquid sodium	from liquid lead-bismuth	from Heat Transfer Oil	from Combusting Particles	from Inert Solid Particles	from Geothermal Resources	from sunlight	Yet To Be Identified Materials	Advanced Nickel Alloys	Conventional Nickel Alloys	Austenitic Stainless Steels	to Water	to Humidified Air	to Dry Air	TIT / °C
Molten Salt Reactor	NE					3											4-5	6-8	6-8	2	2-4	700 to 850
Sodium Fast Reactor (SFR)	NE							3										6-8	6-8	2	2-4	550
Lead Fast Reactor (LFR)	NE								3								4-5	6-8	6-8	2	2-4	550 to 800
Helium Gas Reactor (GFR, VHTR)	NE			4-5											2	3	4-5	6-8	6-8	2	2-4	700 to 1000
Nuclear Shipboard Propulsion	NE																	6-8	6-8			200 to 300
Direct CSP Tower	EE													4-5			4-5	6-8	6-8	2	2-4	500 to 1000
CSP Tower with Thermal Storage	EE						3	2		2		3					4-5	6-8	6-8	2	2-4	500 to 1000
CSP Trough with Thermal Storage	EE						3			2								6-8	6-8	2	2-4	300 to 600
CSP Dish Generator	EE							2		2				4-5			4-5	6-8			2-4	500 to 1000
Direct Geothermal Plant	GT												2					6-8	6-8	2	2-4	100 to 300
Indirect Geothermal Plant	GT				4-5													6-8	6-8	2	2-4	100 to 300
Direct Natural Gas Combustion	FE	3-5	4												2	3	4-5	6-8	6-8	2	2-4	1100 to 1500
Integrated Gasification Coal	FE	3-5													2	3	4-5	6-8	6-8	2	2-4	1100 to 1500
Pulverized Coal Fluidized Bed	FE										4					3	4-5	6-8	6-8	2	2-4	550 to 900
Waste Heat Recovery	FE		4															6-8	6-8	2	2-4	230 to 650
Gas Turbine Bottoming	FE		4															6-8	6-8	2	2-4	230 to 650
Municipal waste to energy	FE		4															6-8	6-8	2	2-4	230 to 650
10 MWe Pilot	FE		4														4-5	6-8	6-8	2	2-4	550 to 700
50 MWe Demonstration	FE		4														4-5	6-8	6-8	2	2-4	550 to 700
		N/A	Gas				Liquid					Solid			>750	750	650	550	sCO2 Cooling			
		sCO2 Heating from Various Sources													Recuperation MDMT / °C							

NE, Peregrine CRADA NEUP NEUP SuNLaMP SERIIUS NE, NEUPs NEUP, APOLLO, NE, CRADAs (VPE, Peregrine)

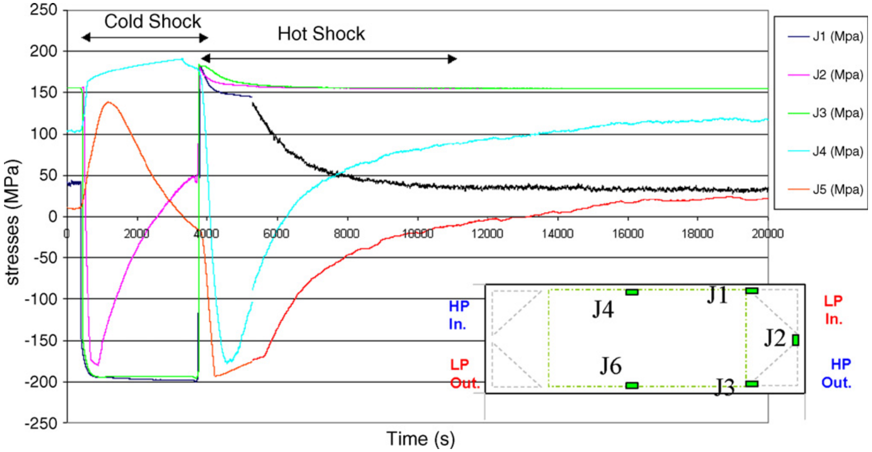
Key Development Metrics

- **Economics**
  - How do we optimize designs and reduce fabrication costs?
    - Efficiency vs. Effectiveness
    - Efficiency vs. pressure drop
    - Manufacturing techniques
- **Failure Modes**
  - How do we accommodate thermal stress and fatigue?
    - Pressure containment (material vs. geometry)
    - Higher Temperatures
    - Corrosion and fouling

Echogen



"[A] 30% reduction in HX cost would have [a] meaningful impact on system cost."



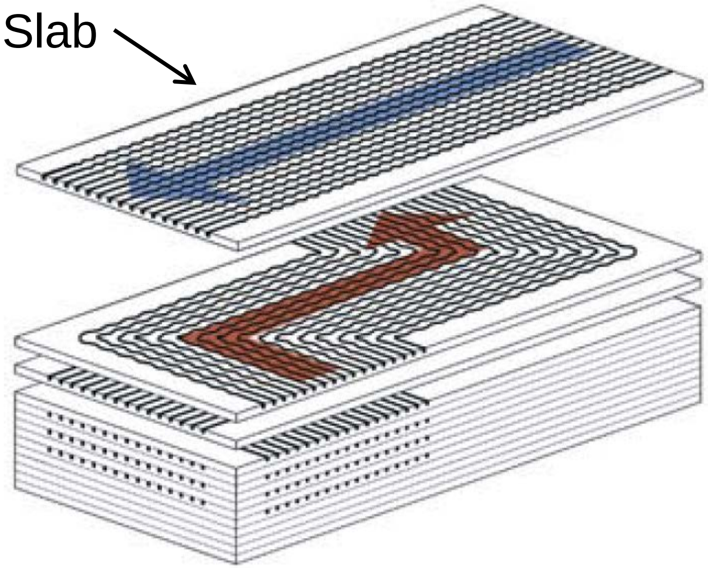
[1] T. Held, "Performance & cost targets for sCO2 heat exchangers," presented at the National Energy Technology Laboratory - EPRI Workshop on Heat Exchangers for Supercritical CO2 Power Cycles, San Diego, CA, USA, 15-Oct-2015.

[2] F. Pra, P. Tochon, C. Mauget, J. Fokkens, and S. Willemsen, "Promising designs of compact heat exchangers for modular HTRs using the Brayton cycle," *Nuclear Engineering and Design*, vol. 238, no. 11, pp. 3160–3173, Nov. 2008.

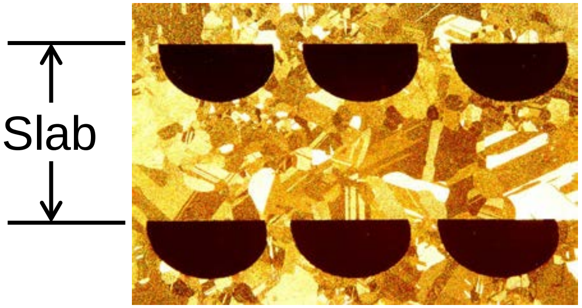
MCHE DESIGN ALGORITHM

The Printed Circuit Heat Exchanger

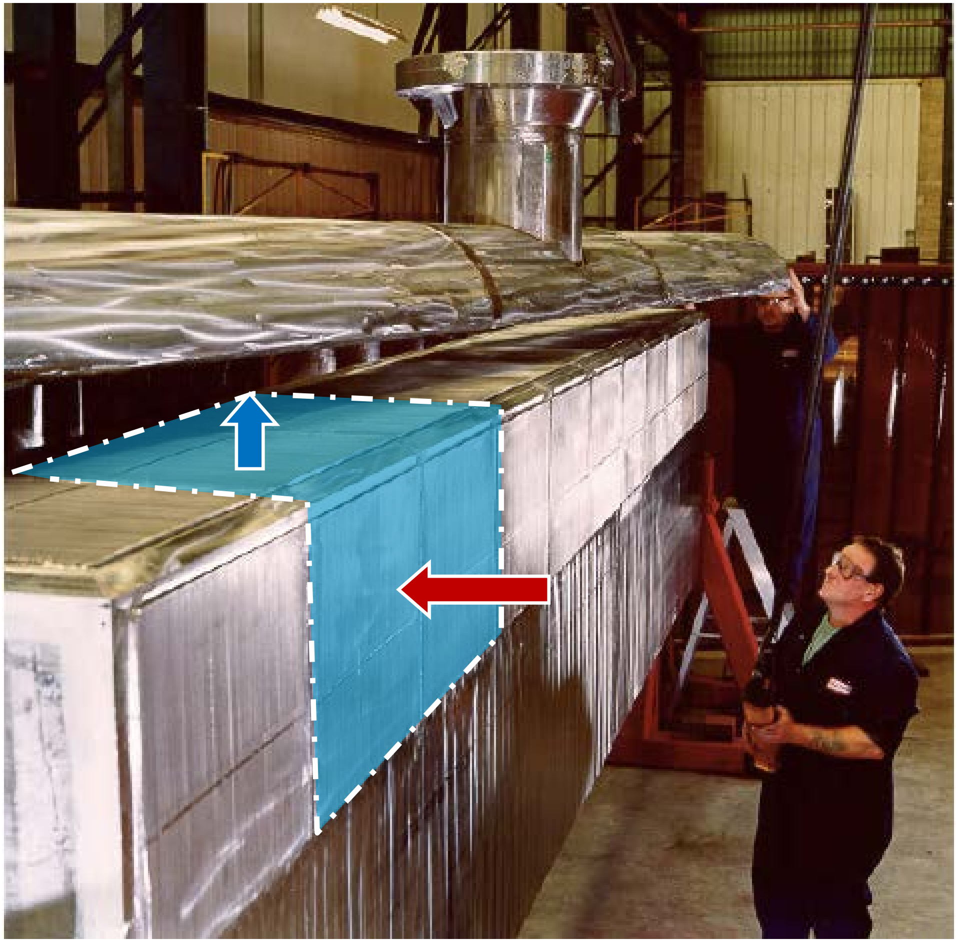
Heat Exchanger Core



Diffusion Bonding



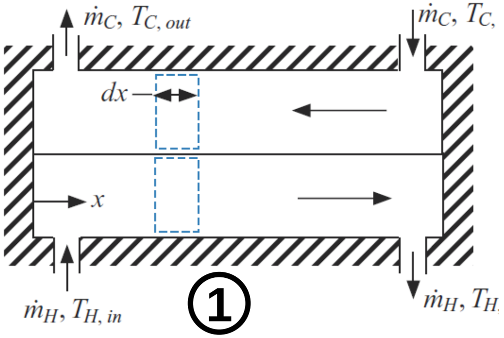
Core and Manifold Assembly



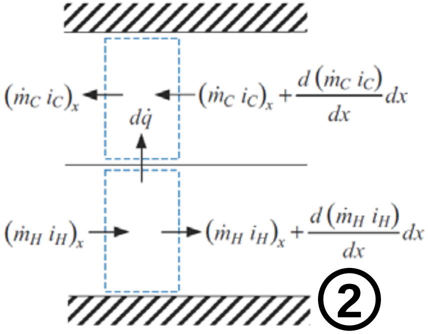
Methods of Heat Exchanger Design

- Effectiveness – NTU / LMTD Methods
  - Uses analytical solutions to various heat exchanger configurations
  - Explicit solution method with reasonable accuracy
- Compact Heat Exchanger Correlations
  - Correlations developed from experimental data for several geometries
  - Explicit accurate solution but for a limited number of correlations
- Sub-Heat Exchanger Method
  - Implements method 1 multiple times to capture property variations
  - Implicit solution needing fewer nodes / iterations than 1D solutions
- 1D Channel Solutions
  - Simulates channels identically or in parallel to determine performance
  - Iterative, intensive solution with the highest accuracy and flexibility
- More complex methods also exist (2D, 3D, CFD)

Effectiveness - NTU Derivation



①



②

③ $$\boxed{\frac{dT_H}{dx} = -\frac{UA}{L\,\dot{m}_H c_H}(T_H - T_C)}$$

③ $$\boxed{\frac{dT_C}{dx} = -\frac{UA}{L\,\dot{m}_C c_C}(T_H - T_C)}$$

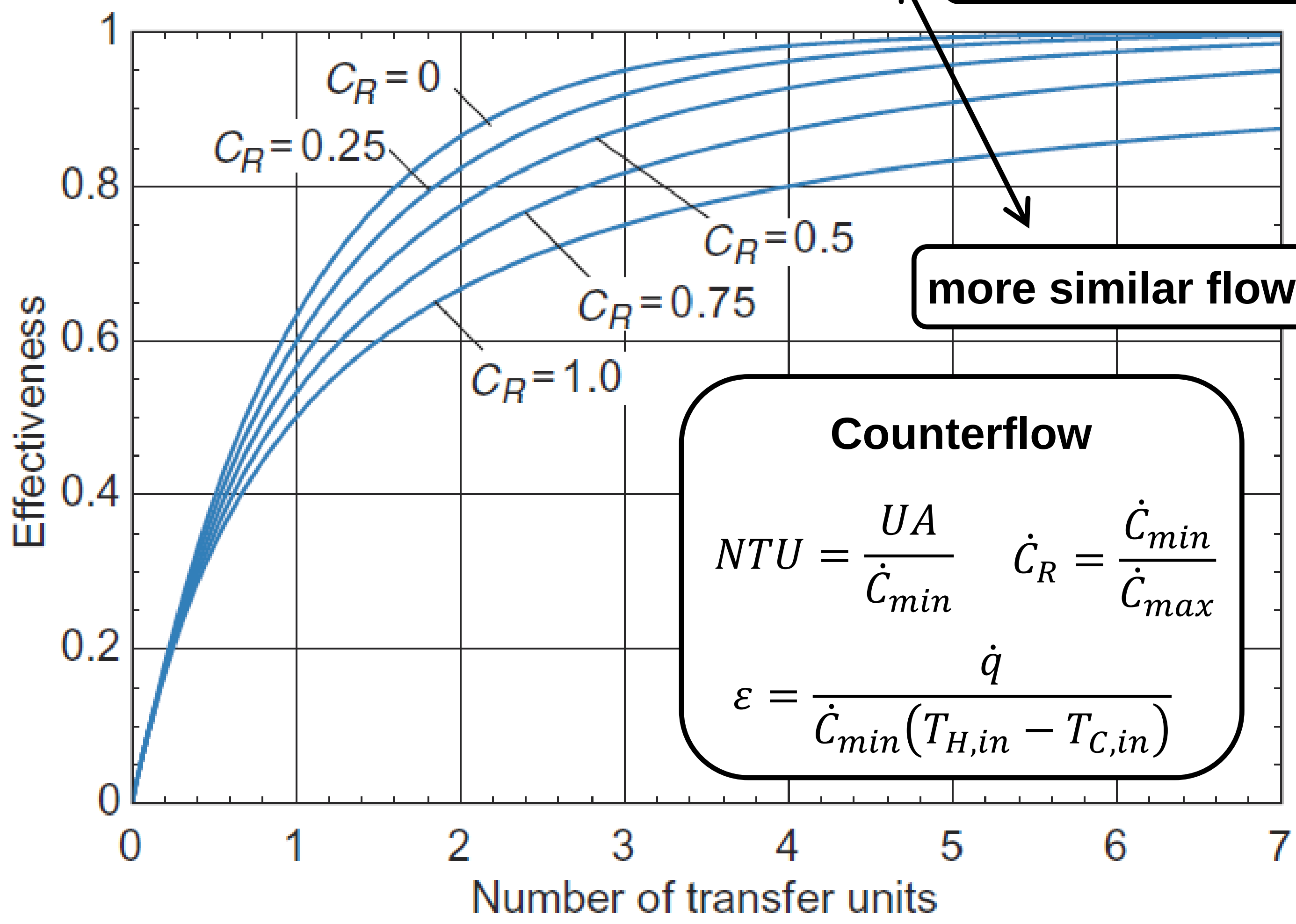
④ $$\boxed{\ln\left(\frac{T_{H,out} - T_{C,in}}{T_{H,in} - T_{C,out}}\right) = -UA\left(\frac{1}{\dot{C}_H} - \frac{1}{\dot{C}_C}\right)}$$

⑤ $$NTU = \begin{cases} \dfrac{\ln\left[\dfrac{1 - \varepsilon\, C_R}{1 - \varepsilon}\right]}{1 - C_R} & \text{for } C_R < 1 \\ \dfrac{\varepsilon}{1 - \varepsilon} & \text{for } C_R = 1 \end{cases}$$

1. Assume:
   - Externally adiabatic
   - Incompressible flow
   - Constant specific heat capacity
   - Enthalpy independent of pressure
2. Finite difference method
   - Establish control volumes
3. Coupled differential equations
   - Hot and cold-side temperatures
4. General solution
   - Relate temperatures, UA, $\dot{C}$’s
5. Effectiveness-NTU formulation
   - $NTU = \frac{UA}{\dot{C}_{min}}$, and $\dot{C}_R = \frac{\dot{C}_{min}}{\dot{C}_{max}}$
   - $\varepsilon = \dot{q}/[\dot{C}_{min}(T_{H,in} - T_{C,in})]$

G. Nellis and S. A. Klein, *Heat Transfer*. Cambridge; New York: Cambridge University Press, 2009.

Effectiveness - NTU Solution



less similar flows

more similar flows

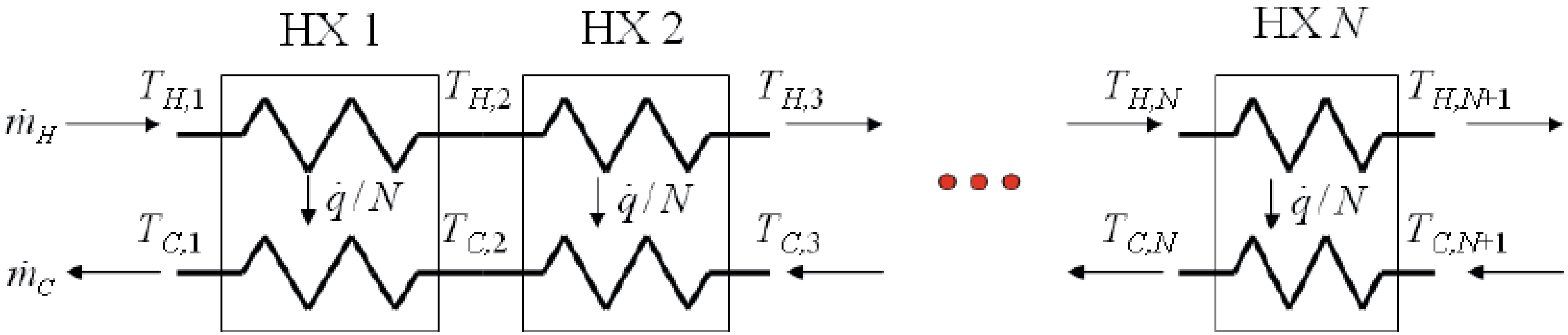
Counterflow

$$NTU = \frac{UA}{\dot{C}_{min}} \qquad \dot{C}_R = \frac{\dot{C}_{min}}{\dot{C}_{max}}$$

$$\varepsilon = \frac{\dot{q}}{\dot{C}_{min}\left(T_{H,in} - T_{C,in}\right)}$$

G. Nellis and S. A. Klein, *Heat Transfer*. Cambridge; New York: Cambridge University Press, 2009.

Sub-Heat Exchanger Method



$$\dot{C}_i = \dot{m}\frac{h_i - h_{i+1}}{\text{MAX}\left(1\text{e}{-4}\ [\text{K}], |T_i - T_{i+1}|\ \text{SIGN}(h_i - h_{i+1})\right)}$$

$$\varepsilon_i = \frac{\dot{q}_i}{\text{MIN}\left(\dot{C}_{A,i}, \dot{C}_{B,i}\right)\left(T_{A,i} - T_{B,i+1}\right)}$$

$$NTU_i = \begin{cases} \dfrac{\ln\left[\dfrac{(1-\varepsilon C_R)}{1-\varepsilon}\right]}{1-C_R} & \text{for } C_R < 1 \\ \dfrac{\varepsilon}{1-\varepsilon} & \text{for } C_R = 1 \end{cases}$$

$$UA_i = NTU_i\ \text{MIN}\left(\dot{C}_{A,i}, \dot{C}_{B,i}\right)$$

- Divide into a series of HXers
- Extends e-NTU method
- Assumptions apply to each sub-heat exchanger (Δx)
- Best method to obtain UA accurately and quickly with variable property flows

G. Nellis and S. A. Klein, *Heat Transfer*. Cambridge; New York: Cambridge University Press, 2009.

ASME BPVC Design Equations

$$S_{m,stay} = \frac{Ph}{2t_4}\left[\frac{6+K(11-\alpha^2)}{3+5K}\right]$$

$$S_{m,1} = \frac{Ph}{2t_1}\left[3-\frac{6+K(11-\alpha^2)}{3+5K}\right]$$

$$S_{m,2} = \frac{PH}{2t_2}$$

$$S_{b,stay} = 0$$

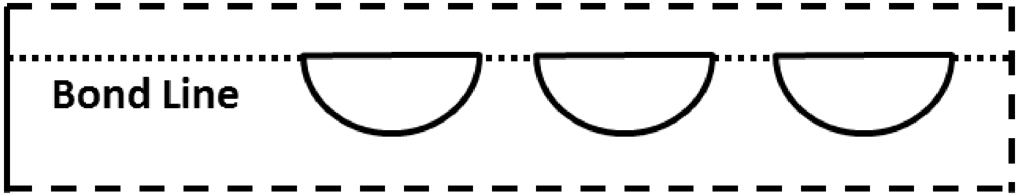
$$\left(S_{b,1}\right)_{at\,N} = \frac{Pc_1}{24I_1}\left[-3H^2+2h^2\left(\frac{3+5\alpha^2K}{3+5K}\right)\right]$$

$$\left(S_{b,1}\right)_{at\,Q} = \frac{Ph^2c_1}{12I_1}\left(\frac{3+5\alpha^2K}{3+5K}\right)$$

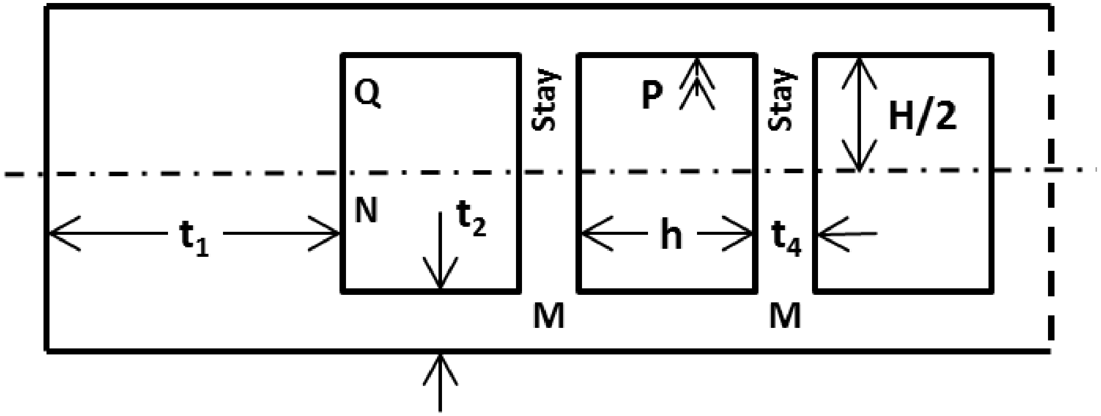
$$\left(S_{b,2}\right)_{at\,M} = \frac{Ph^2c_2}{12I_2}\left[\frac{3+K(6-\alpha^2)}{3+5K}\right]$$

$$\left(S_{b,2}\right)_{at\,Q} = \frac{Ph^2c_2}{12I_2}\left(\frac{3+5\alpha^2K}{3+5K}\right)$$

Section of a printed circuit heat exchanger



Vessel sketch from the ASME BPVC VIII-1-13-2(a)(8)



M. Carlson, T. Conboy, D. Fleming, and J. Pasch, “Scaling Considerations for SCO2 Cycle Heat Exchangers,” in *Proceedings of the ASME Turbo Expo 2014: Turbine Technical Conference and Exposition*, Düsseldorf, Germany, 2014, pp. 1–5.

Non-Dimensionalized Equations

$$\frac{P}{SE} \le \left(\frac{1}{wf} - 1\right)$$

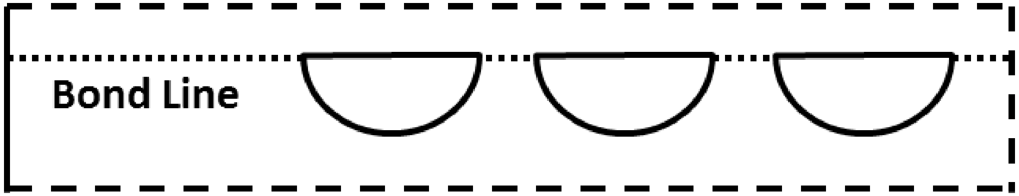
$$\frac{P}{S} \le 2\left(\frac{1}{df} - 1\right)$$

$$\frac{P}{S} \le 3\left(\frac{df}{1-df} + \frac{1}{AR^2}\left(\frac{df}{1-df}\right)^2\right)^{-1}$$

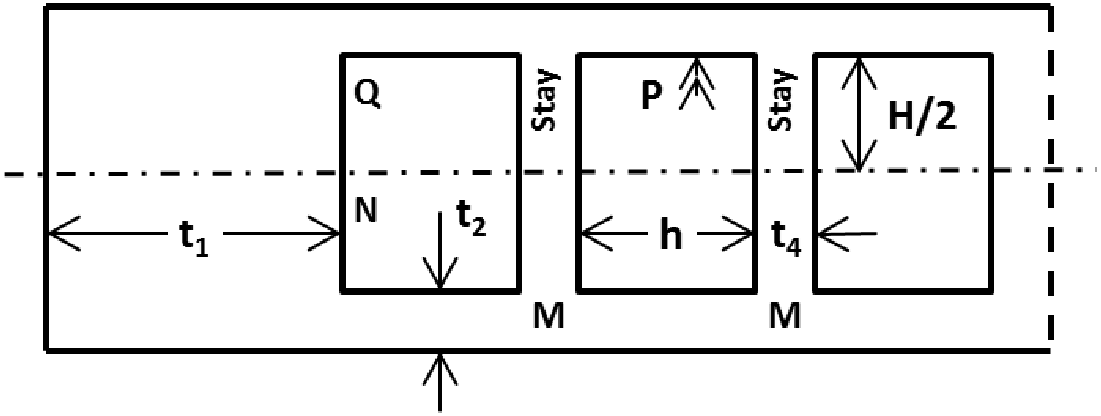
$$wf = \frac{h}{h + t_4}$$

$$df = \frac{H}{H + t_2}$$

Section of a printed circuit heat exchanger

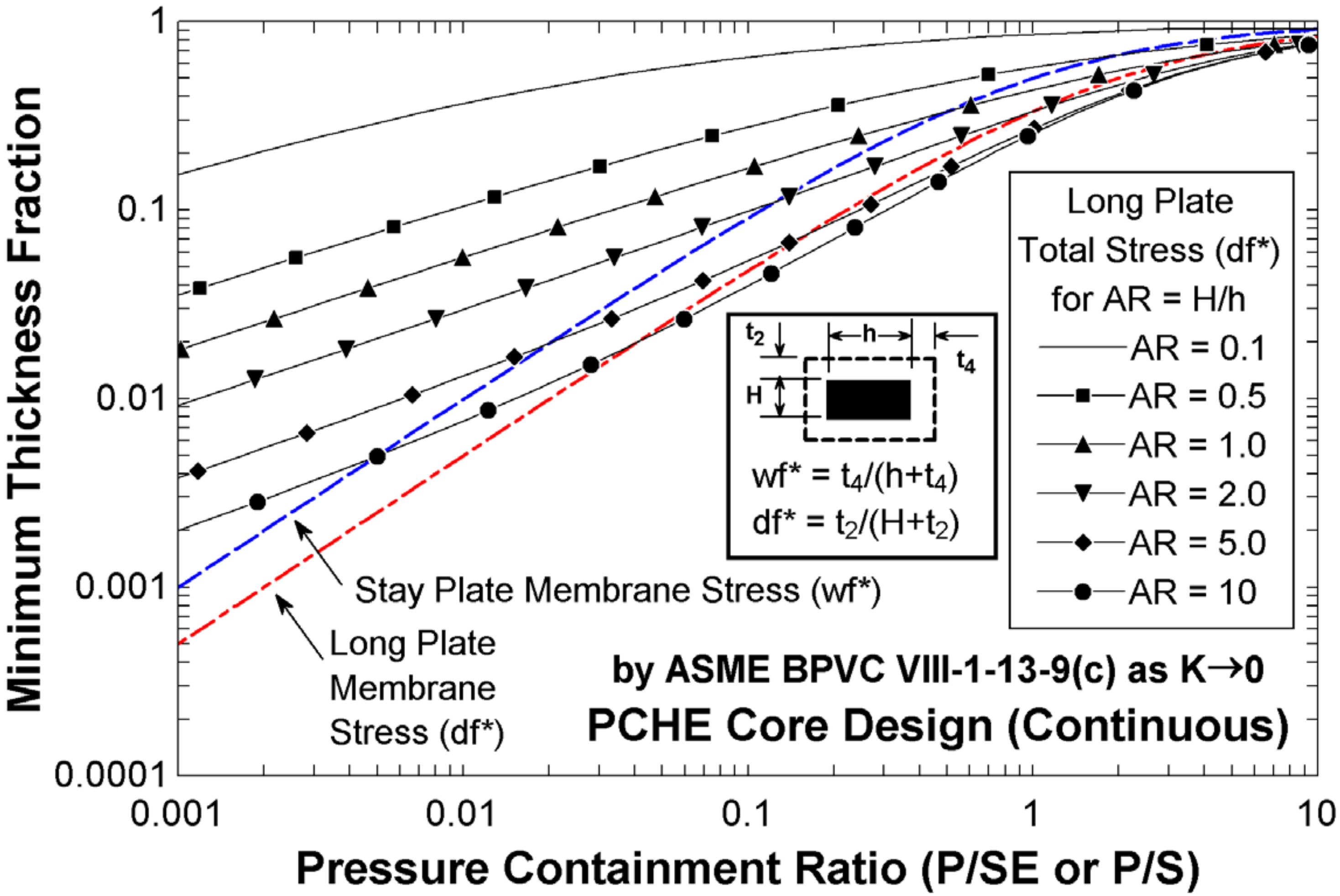


Vessel sketch from the ASME BPVC VIII-1-13-2(a)(8)



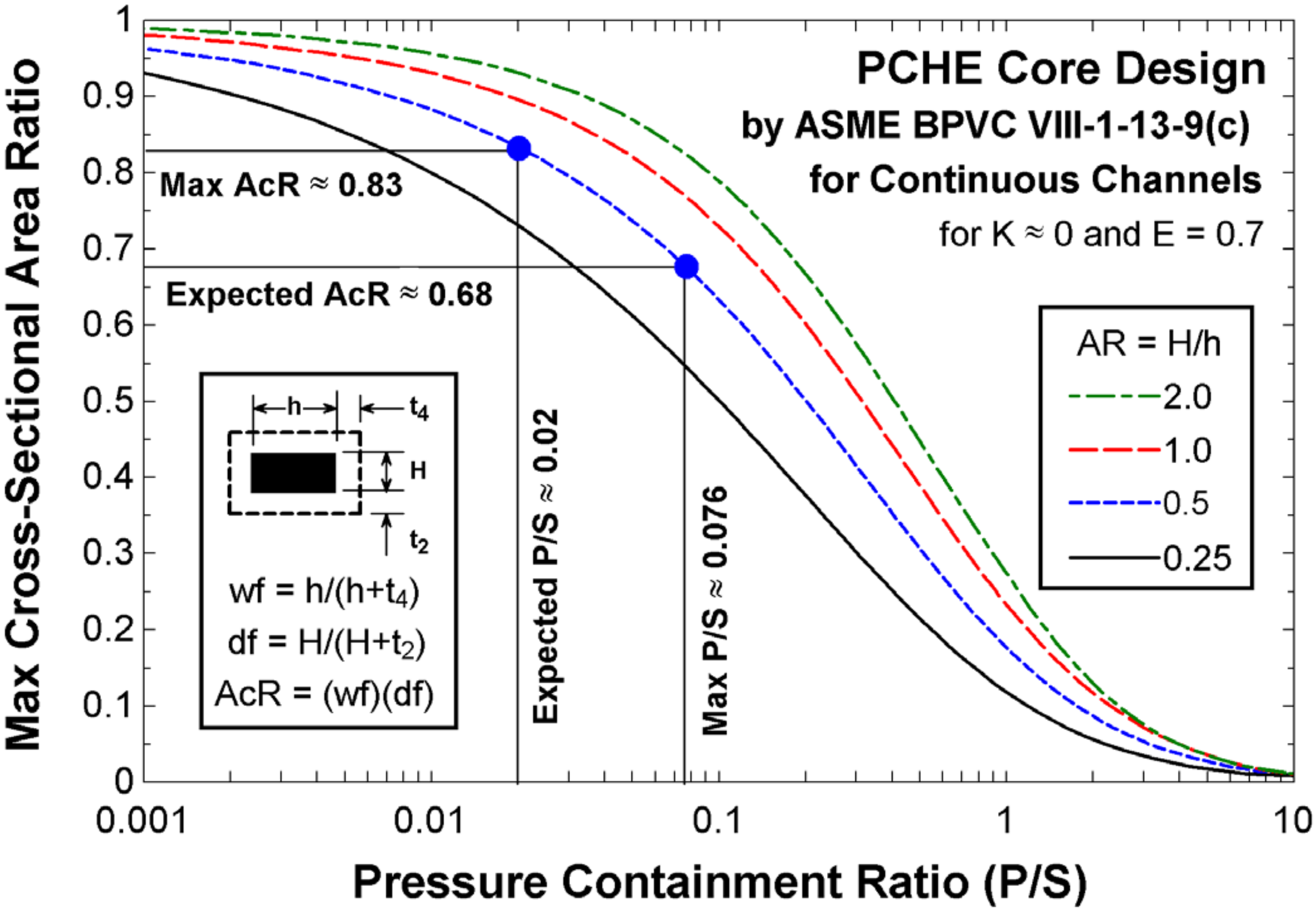
M. Carlson, T. Conboy, D. Fleming, and J. Pasch, “Scaling Considerations for SCO2 Cycle Heat Exchangers,” in *Proceedings of the ASME Turbo Expo 2014: Turbine Technical Conference and Exposition*, Düsseldorf, Germany, 2014, pp. 1–5.

PCHE Core Pressure Containment



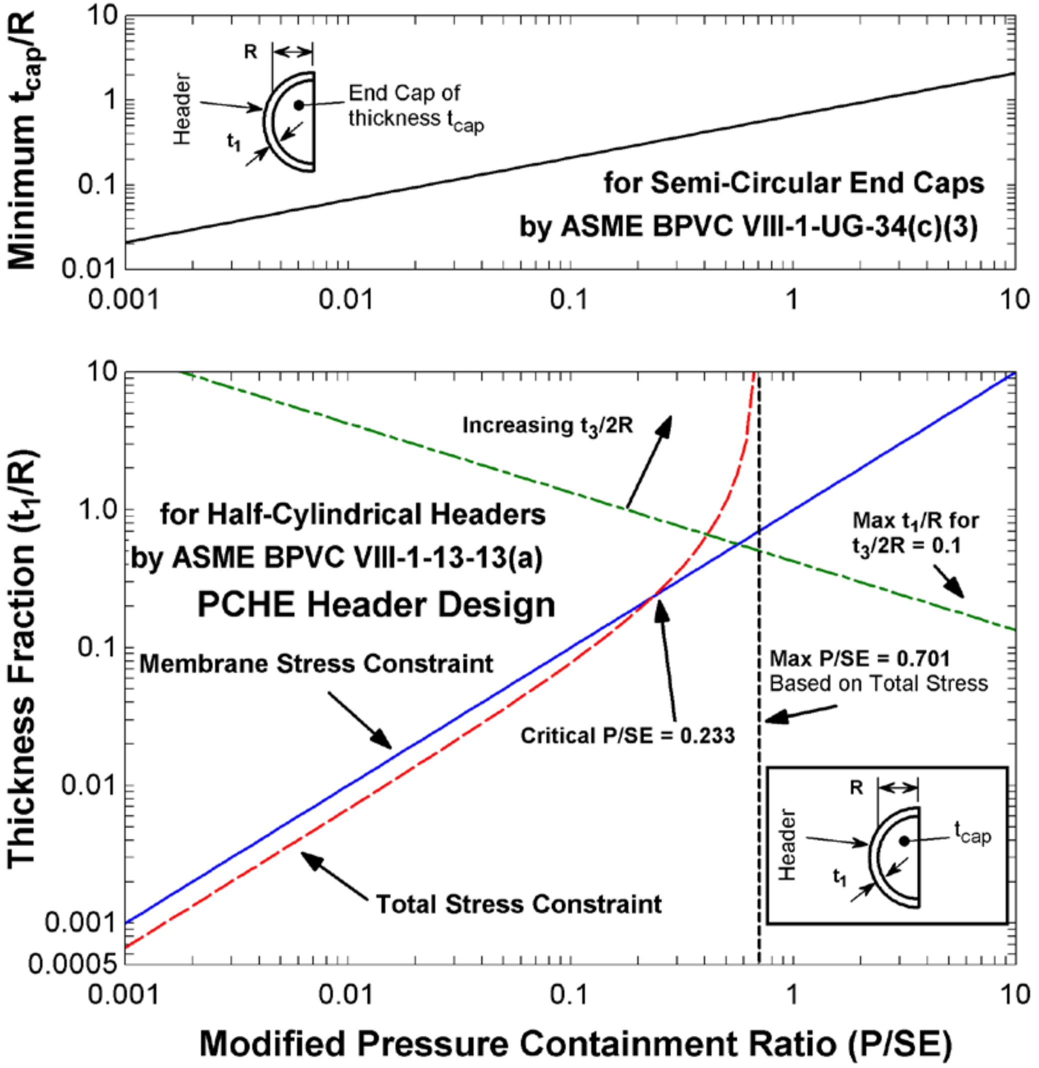
M. Carlson, T. Conboy, D. Fleming, and J. Pasch, “Scaling Considerations for SCO2 Cycle Heat Exchangers,” in *Proceedings of the ASME Turbo Expo 2014: Turbine Technical Conference and Exposition*, Düsseldorf, Germany, 2014, pp. 1–5.

PCHE Core Pressure Containment



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.

Half-Cylindrical Headers



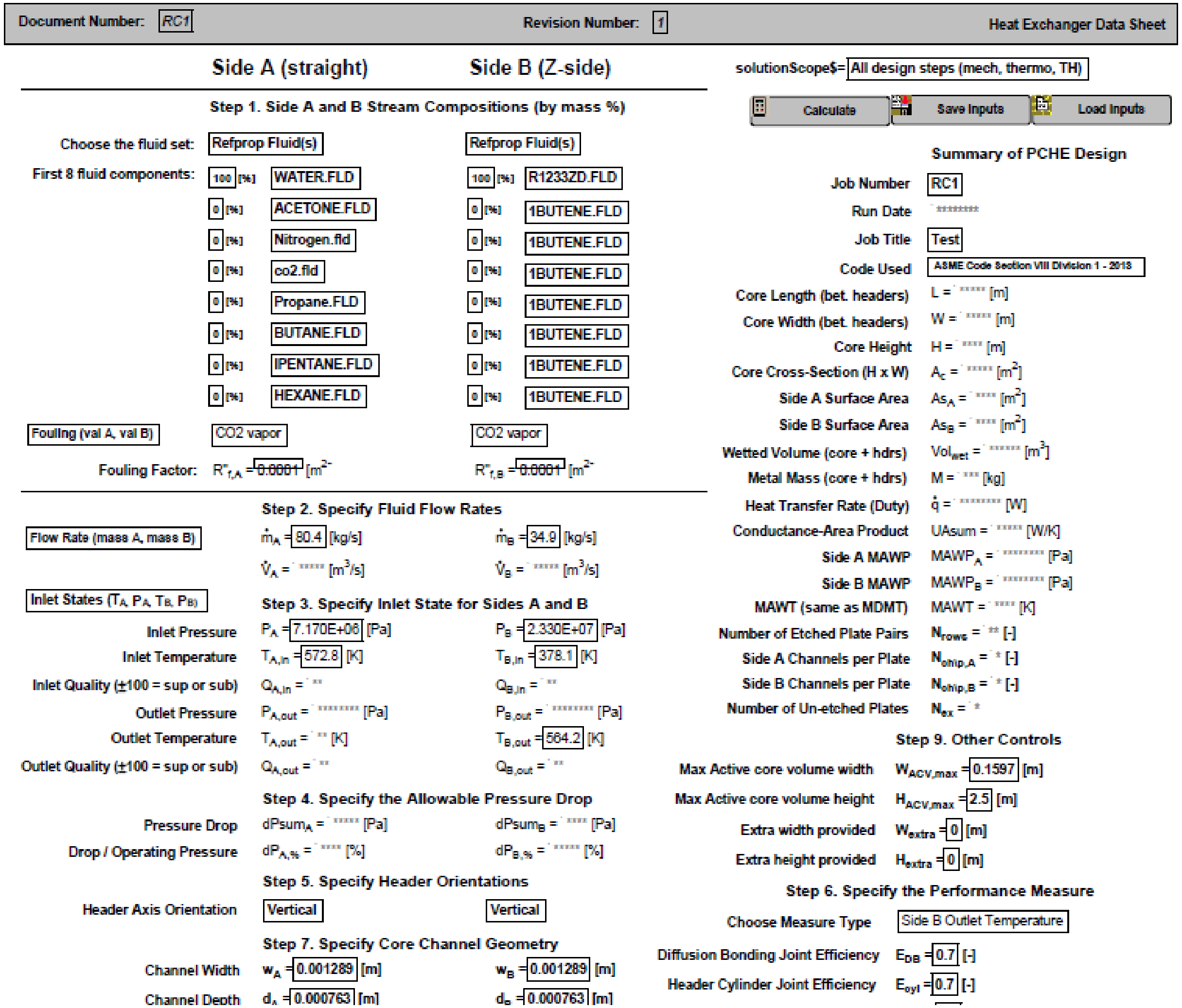
Thermal-Hydraulics

$$\underset{\textcircled{1}}{\Delta x_i} = \underset{\textcircled{2}}{UA_i}\left(\underset{\textcircled{3}}{\frac{1}{h_{A,i}N_{ch,A}p_{ch,A}}} + \underset{\textcircled{5}}{\frac{R^{''}_{f,A,i}}{N_{ch,A}p_{ch,A}}} + \underset{\textcircled{4}}{\frac{t_m}{k_{m,i}W}} + \underset{\textcircled{3}}{\frac{1}{h_{B,i}N_{ch,B}p_{ch,B}}} + \underset{\textcircled{5}}{\frac{R^{''}_{f,B,i}}{N_{ch,B}p_{ch,B}}}\right)$$

1. Sub-heat exchanger length
2. Sub-heat exchanger conductance-area product
3. Convective thermal resistances
4. Conductive thermal resistance
5. Fouling thermal resistances

PCHE Design Software

- **Sub-hxer model**
- **ASME BPVC**
- **Single, two-phase, supercritical flows**
- **Over 400 fluids**



Document Number: RC1

Revision Number: 1

Heat Exchanger Data Sheet

solutionScope$= All design steps (mech, thermo, TH)

	Side A (straight)		Side B (Z-side)	
Step 1. Side A and B Stream Compositions (by mass %)				
Choose the fluid set:	Refprop Fluid(s)		Refprop Fluid(s)	
First 8 fluid components:	100 [%]	WATER.FLD	100 [%]	R1233ZD.FLD
	0 [%]	ACETONE.FLD	0 [%]	1BUTENE.FLD
	0 [%]	Nitrogen.fld	0 [%]	1BUTENE.FLD
	0 [%]	co2.fld	0 [%]	1BUTENE.FLD
	0 [%]	Propane.FLD	0 [%]	1BUTENE.FLD
	0 [%]	BUTANE.FLD	0 [%]	1BUTENE.FLD
	0 [%]	IPENTANE.FLD	0 [%]	1BUTENE.FLD
	0 [%]	HEXANE.FLD	0 [%]	1BUTENE.FLD
Fouling (val A, val B)	CO2 vapor		CO2 vapor	
Fouling Factor:	$R''_{f,A}$ = 0.0001 $[m^{2-}$		$R''_{f,B}$ = 0.0001 $[m^{2-}$	

Step 2. Specify Fluid Flow Rates

Flow Rate (mass A, mass B)	$\dot{m}_A$ = 80.4 [kg/s]	$\dot{m}_B$ = 34.9 [kg/s]
	$\dot{V}_A$ = ***** $[m^3/s]$	$\dot{V}_B$ = ***** $[m^3/s]$

Step 3. Specify Inlet State for Sides A and B

Inlet States (T_A, P_A, T_B, P_B)		
Inlet Pressure	P_A = 7.170E+06 [Pa]	P_B = 2.330E+07 [Pa]
Inlet Temperature	$T_{A,in}$ = 572.8 [K]	$T_{B,in}$ = 378.1 [K]
Inlet Quality (±100 = sup or sub)	$Q_{A,in}$ = **	$Q_{B,in}$ = **
Outlet Pressure	$P_{A,out}$ = ******** [Pa]	$P_{B,out}$ = ******** [Pa]
Outlet Temperature	$T_{A,out}$ = ** [K]	$T_{B,out}$ = 564.2 [K]
Outlet Quality (±100 = sup or sub)	$Q_{A,out}$ = **	$Q_{B,out}$ = **

Step 4. Specify the Allowable Pressure Drop

Pressure Drop	$dPsum_A$ = ***** [Pa]	$dPsum_B$ = **** [Pa]
Drop / Operating Pressure	$dP_{A,\%}$ = **** [%]	$dP_{B,\%}$ = ***** [%]

Step 5. Specify Header Orientations

Header Axis Orientation	Vertical	Vertical

Step 7. Specify Core Channel Geometry

Channel Width	w_A = 0.001289 [m]	w_B = 0.001289 [m]
Channel Depth	d_A = 0.000763 [m]	d_B = 0.000763 [m]

Summary of PCHE Design

Job Number	RC1
Run Date	********
Job Title	Test
Code Used	ASME Code Section VIII Division 1 - 2013
Core Length (bet. headers)	L = ***** [m]
Core Width (bet. headers)	W = ***** [m]
Core Height	H = **** [m]
Core Cross-Section (H x W)	A_c = ***** $[m^2]$
Side A Surface Area	As_A = **** $[m^2]$
Side B Surface Area	As_B = **** $[m^2]$
Wetted Volume (core + hdrs)	Vol_{wet} = ****** $[m^3]$
Metal Mass (core + hdrs)	M = *** [kg]
Heat Transfer Rate (Duty)	$\dot{q}$ = ******** [W]
Conductance-Area Product	UAsum = ***** [W/K]
Side A MAWP	$MAWP_A$ = ******** [Pa]
Side B MAWP	$MAWP_B$ = ******** [Pa]
MAWT (same as MDMT)	MAWT = **** [K]
Number of Etched Plate Pairs	N_{rows} = ** [-]
Side A Channels per Plate	$N_{chip,A}$ = * [-]
Side B Channels per Plate	$N_{chip,B}$ = * [-]
Number of Un-etched Plates	N_{ex} = *

Step 9. Other Controls

Max Active core volume width	$W_{ACV,max}$ = 0.1597 [m]
Max Active core volume height	$H_{ACV,max}$ = 2.5 [m]
Extra width provided	W_{extra} = 0 [m]
Extra height provided	H_{extra} = 0 [m]

Step 6. Specify the Performance Measure

Choose Measure Type	Side B Outlet Temperature
Diffusion Bonding Joint Efficiency	E_{DB} = 0.7 [-]
Header Cylinder Joint Efficiency	E_{cyl} = 0.7 [-]

PROTOTYPE PCHE DESIGN

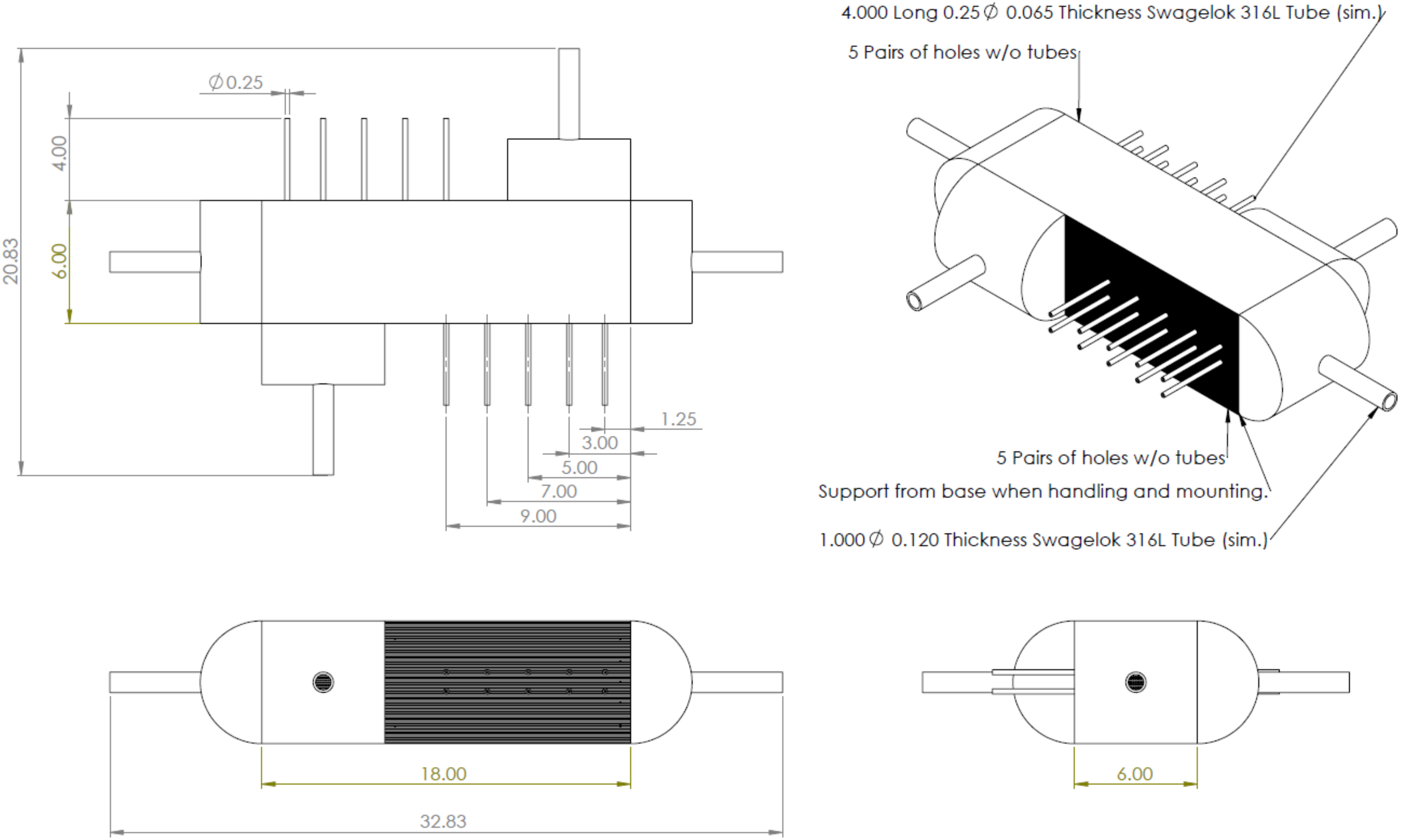
Heat Exchanger Data Sheet

Parameter	Unit	Side A (Straight)	Side B (Z)
Fluid	-	water	water
Mass Flow Rate	kg/s (lbm/hr)	1.5 (12000)	1.5 (12000)
Volumetric Flow Rate	m^3/s (gpm)	1.5e-3 (24)	1.5e-3 (24)
Inlet Temperature	°C (°F)	82 (180)	37 (98)
Inlet Pressure	kPa (psi)	300 (44)	300 (44)
Pressure Drop	kPa (psi)	55 (7.9)	62 (9.0)
Fouling Factor	m^2-K/W	8e-5	8e-5
MAWP	MPa (psi)	20 (2900)	
MAWT	°C (°F)	550 (1000)	
Duty	kW_{th} (Btu/hr)	103 (350000)	
Height x Width x Length	m (in)	0.15 x 0.15 x 0.46 (6 x 6 x 18)	
Active Surface Area	m^2 (in^2)	1.2 (13)	
Material	-	316L Stainless Steel	

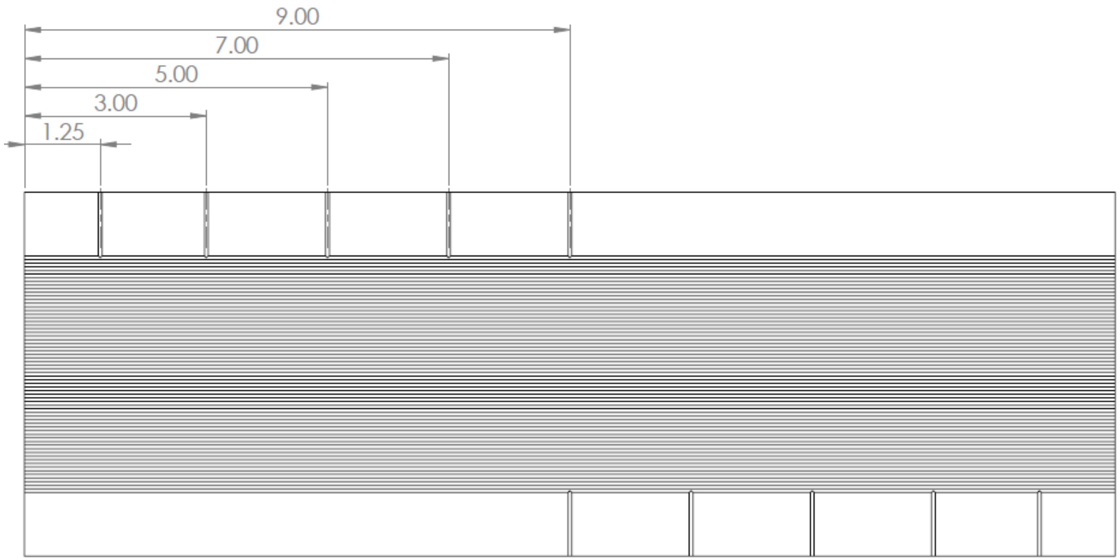
Design for Multiple Phases

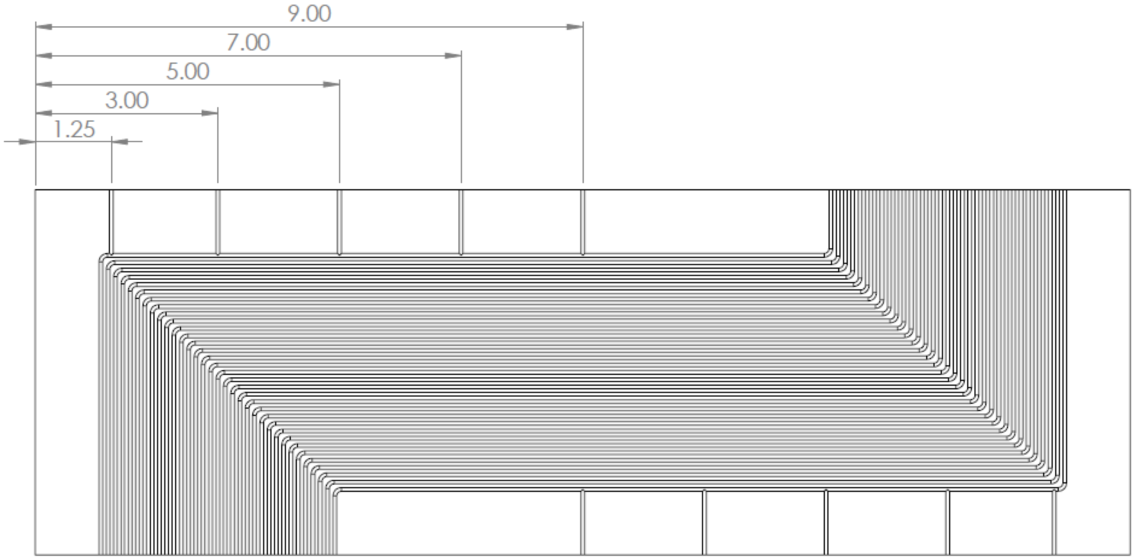
1. Pressure Containment
   - Evaluated by hydrostatic pressure testing
2. Single-phase Thermal Hydraulics
   - Evaluated in the NESL water test loop
3. Supercritical Thermal Hydraulics
   - Evaluated in the NESL sCO2 loop
4. Fatigue Lifetime (to failure)
   - Tested by thermal cycling under pressure

Instrumentation



Instrumentation – Tap Locations

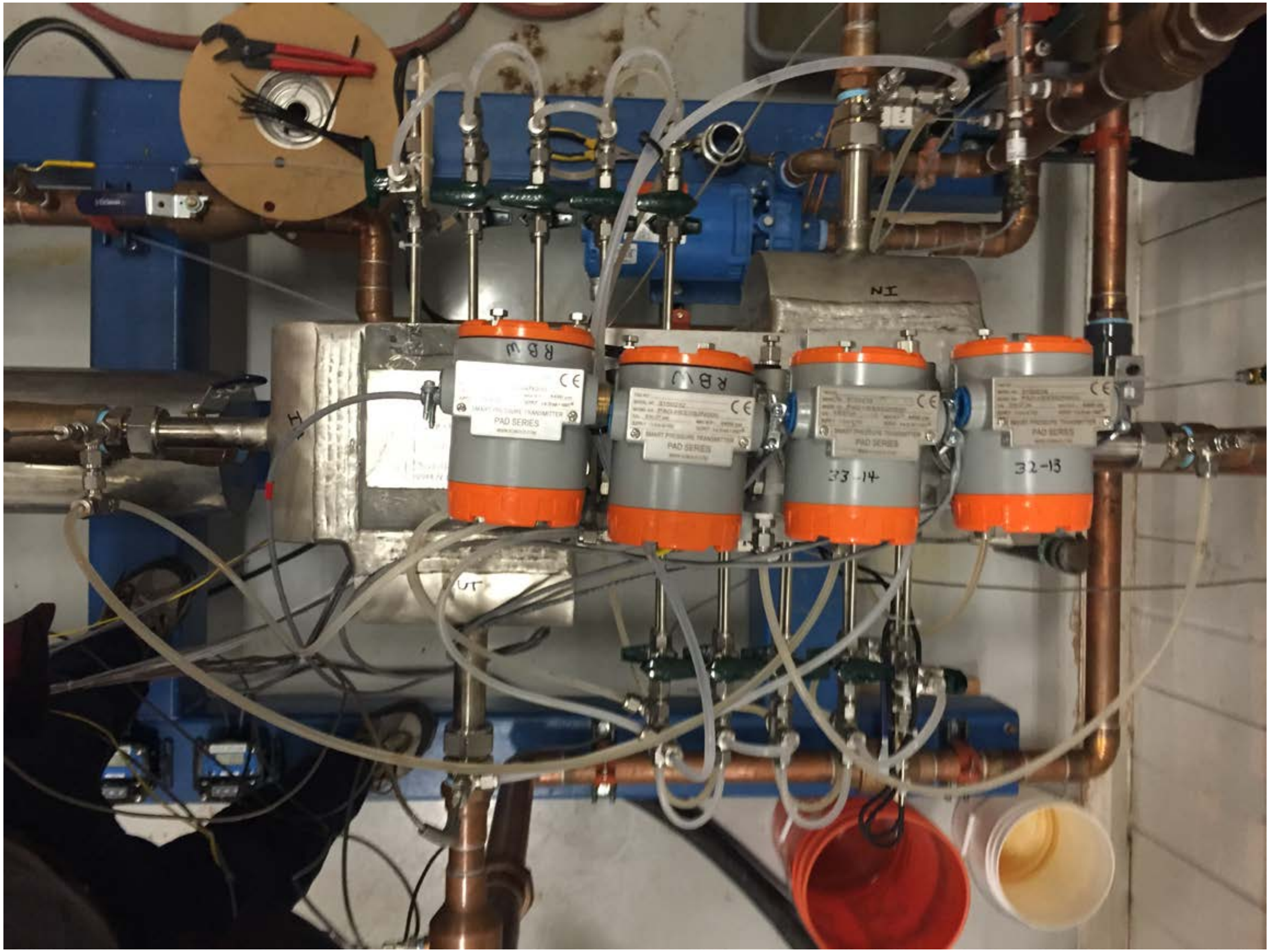




HEAT EXCHANGER TEST PLATFORM

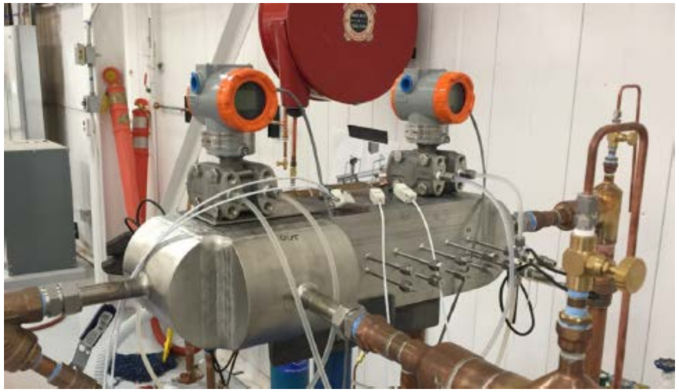
Test Platform Configuration

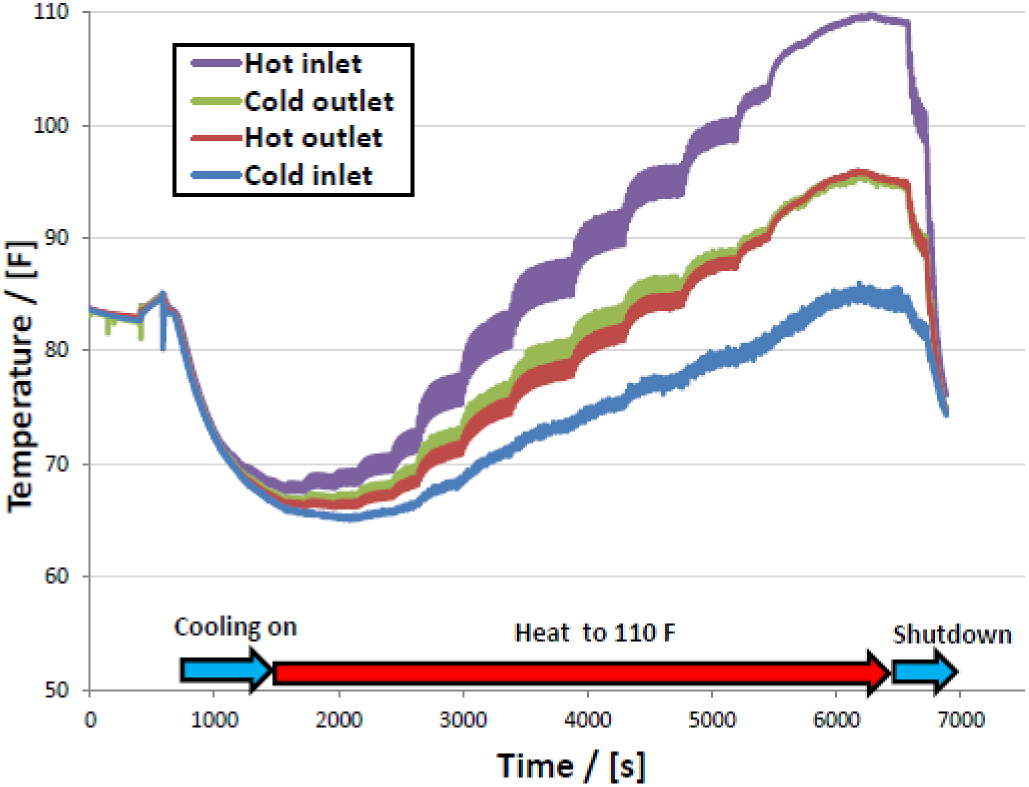
PCHE Instrumentation



PCHE PERFORMANCE COMPARISON

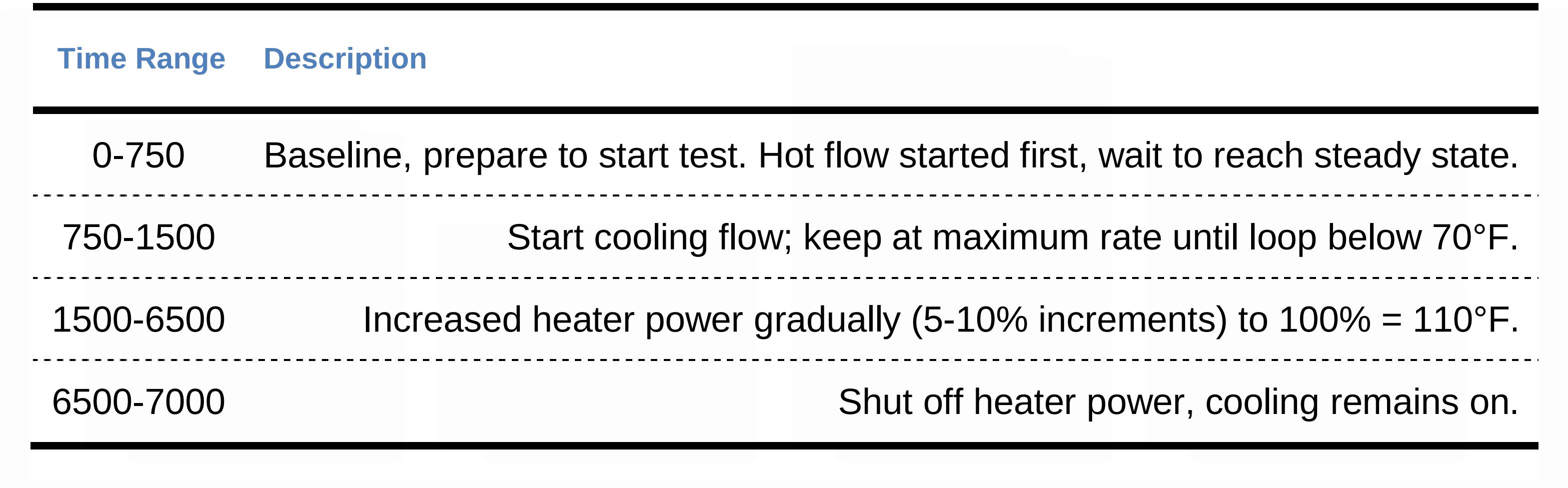
Performance Testing



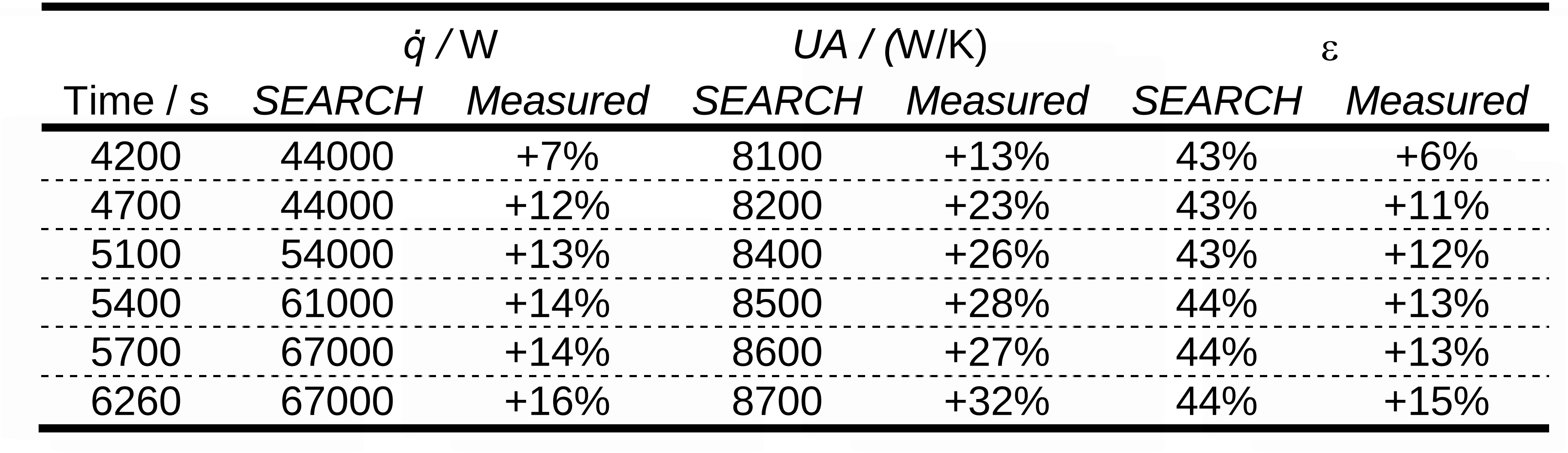


SEARCH appears conservative by at least 10% on q, UA, effectiveness

Performance Comparison



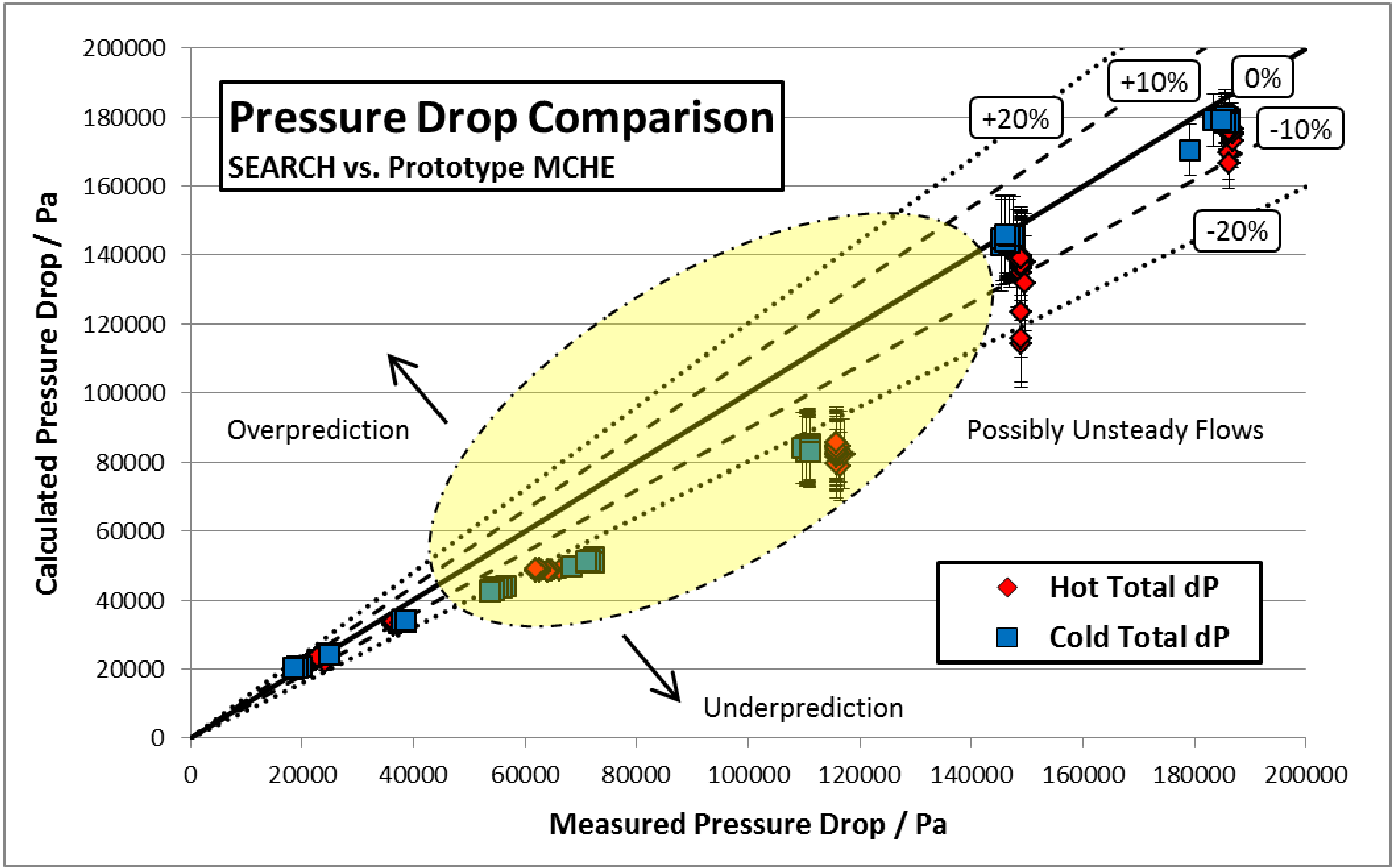
Time Range	**Description**
0-750	Baseline, prepare to start test. Hot flow started first, wait to reach steady state.
750-1500	Start cooling flow; keep at maximum rate until loop below 70°F.
1500-6500	Increased heater power gradually (5-10% increments) to 100% = 110°F.
6500-7000	Shut off heater power, cooling remains on.



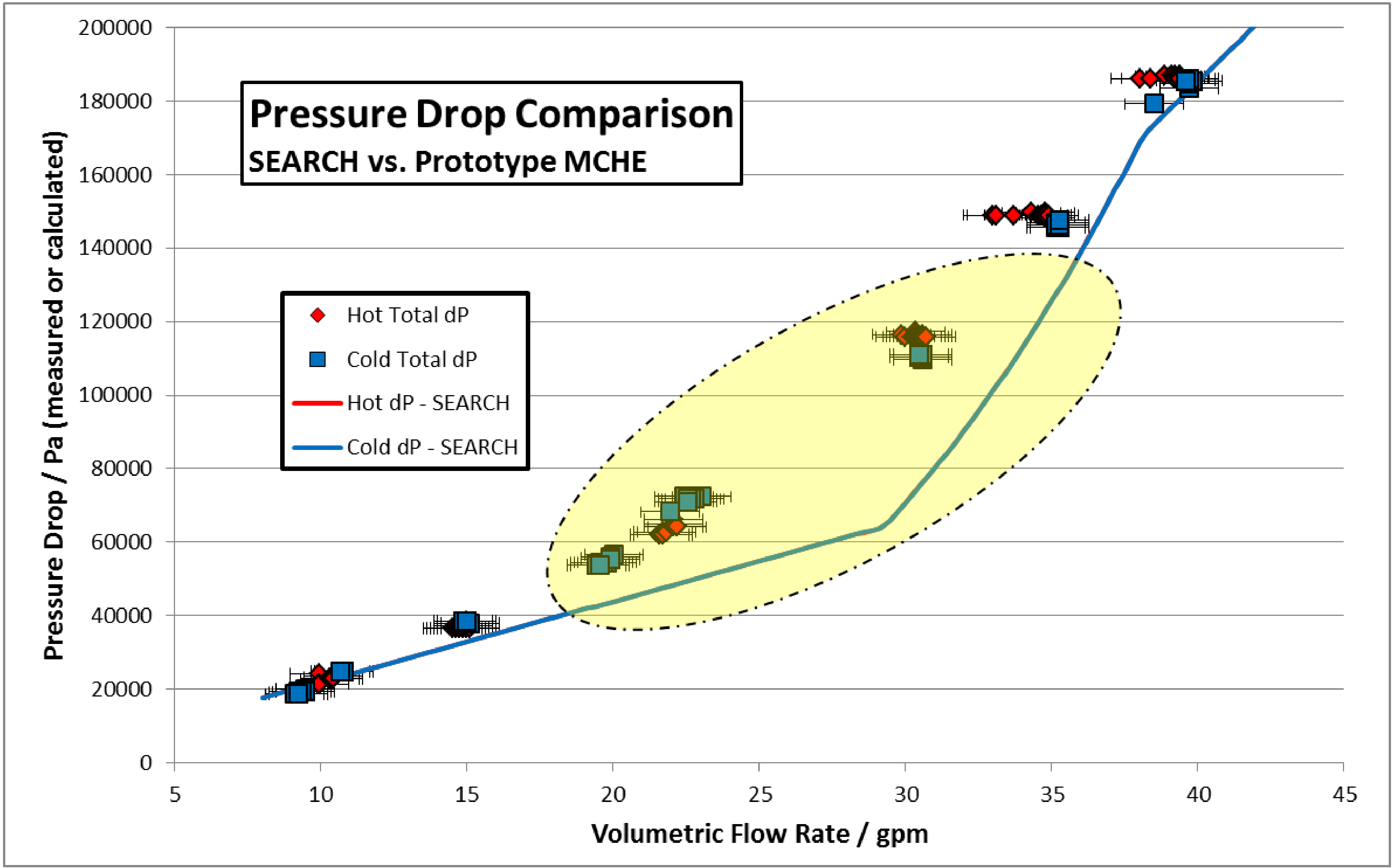
	$\dot{q}$ / W		*UA* / (W/K)		ε	
Time / s	*SEARCH*	*Measured*	*SEARCH*	*Measured*	*SEARCH*	*Measured*
4200	44000	+7%	8100	+13%	43%	+6%
4700	44000	+12%	8200	+23%	43%	+11%
5100	54000	+13%	8400	+26%	43%	+12%
5400	61000	+14%	8500	+28%	44%	+13%
5700	67000	+14%	8600	+27%	44%	+13%
6260	67000	+16%	8700	+32%	44%	+15%

Calculated vs. Meas. Pressure Drop

Sandia National Laboratories



Pressure Drop Prediction Capability



Conclusions

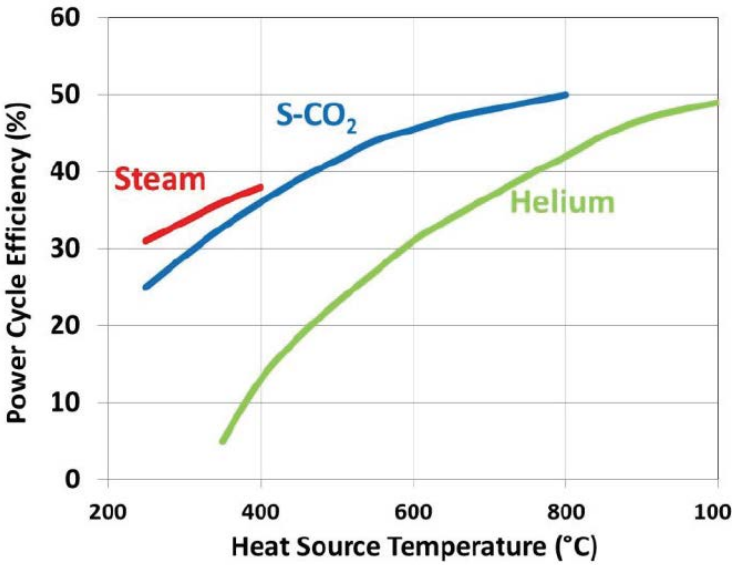
- Based on our first set of tests:
    - SEARCH is within 25% accuracy on key metrics
    - Thermal performance is predicted conservatively
    - Pressure drop is under-predicted in some regimes
- These results have already been applied
- Testing is planned after loop upgrades
    - Additional thermal-hydraulic observations
    - Intermediate state (T & P) profiles
    - Future test phases (sCO2, fatigue)

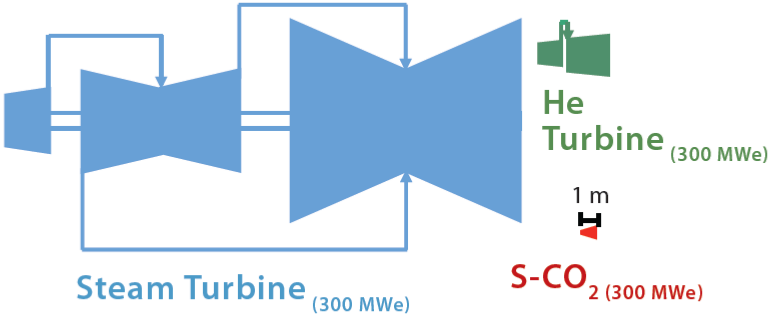
BACKUP SLIDES

The Argument for SCO2 Brayton

Versus Helium and Steam

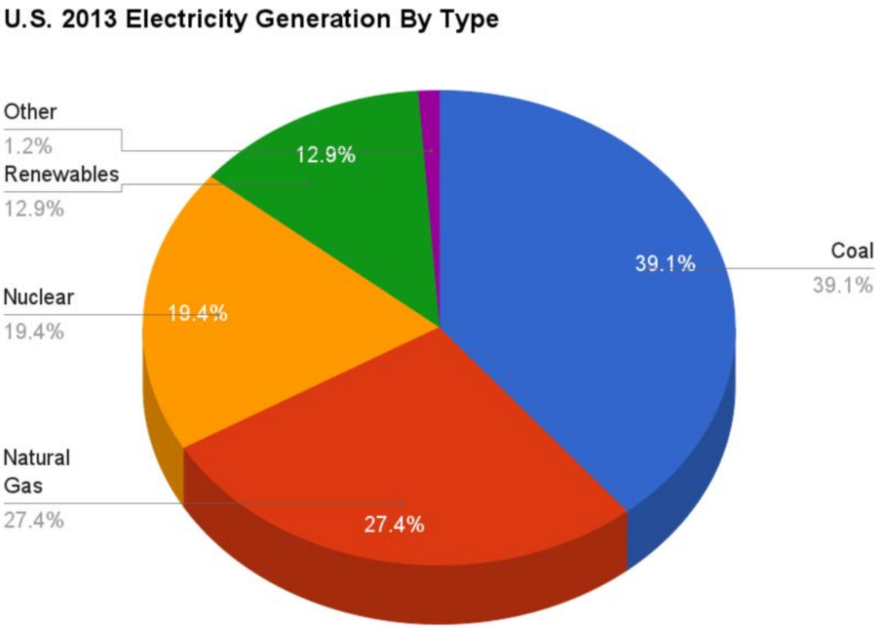
1. Higher efficiency
   - Sodium Fast Reactor operating at 550 °C
   - Concentrated Solar Power up to 700 °C
   - CCS Gasified Coal and Natural Gas up to 1150 °C
2. Compact turbomachinery
   - Smaller system footprint
   - Possibly reduced cost

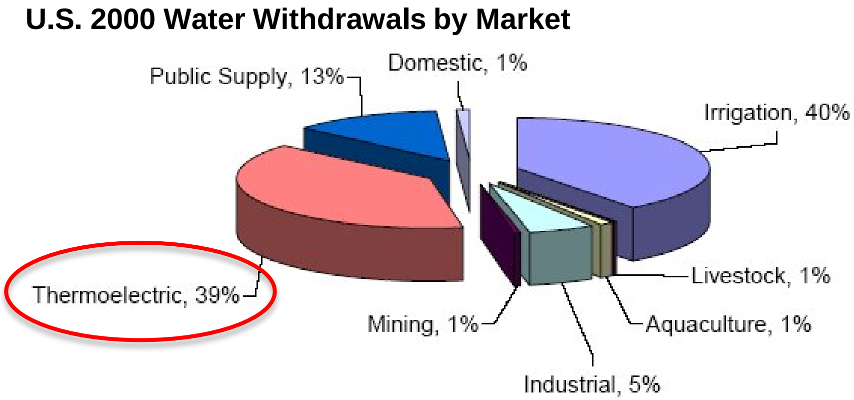




Current Electrical Generation

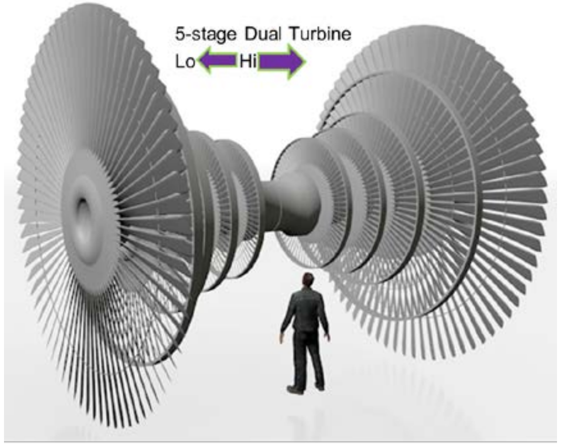
- Electrical Generation
  - Dominated by fossil
  - Nuclear is a critical part
  - Expected that natural gas and nuclear will grow; coal will shrink
- Two main technologies
  - Steam Rankine cycle
    - Coal, Nuclear, CCNG
  - Gas Brayton cycle
    - Natural gas



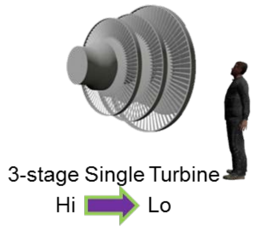


Supercritical CO_2 (sCO_2) Brayton Cycle

- Key Advantages over Steam
  - Smaller turbomachinery
  - Single-phase fluid (no quality issues)
  - Recuperation becomes practical

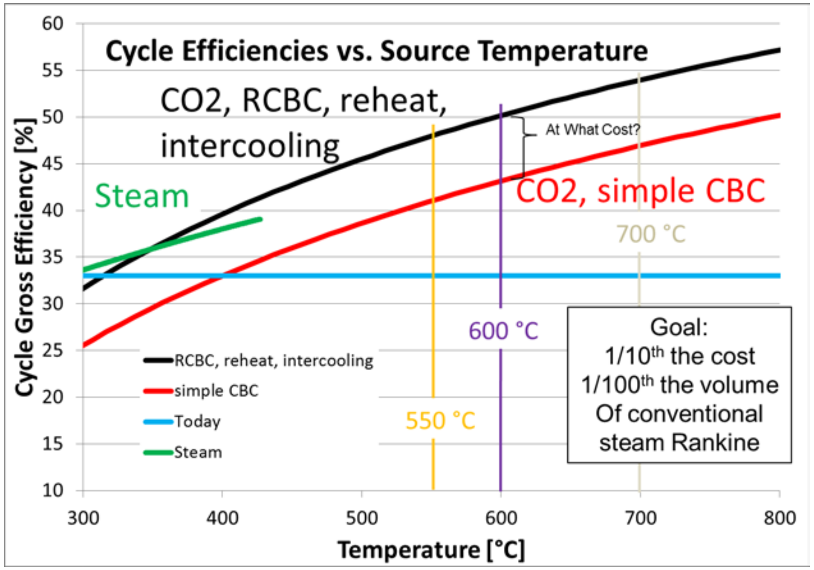


20 meter Steam Turbine (300 MWe)
(Rankine Cycle)



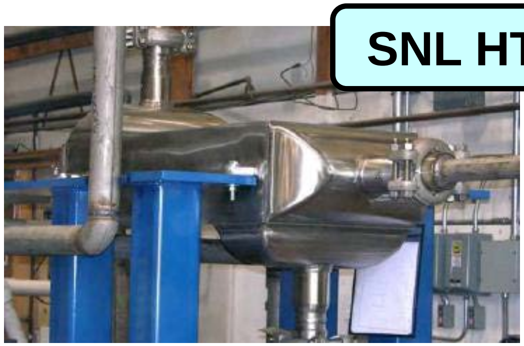
1 meter sCO_2 (300 MWe)
(Brayton Cycle)

- Key Advantages over Gas
  - High efficiency at low temperatures
  - Lower compression work
  - Smaller turbomachinery

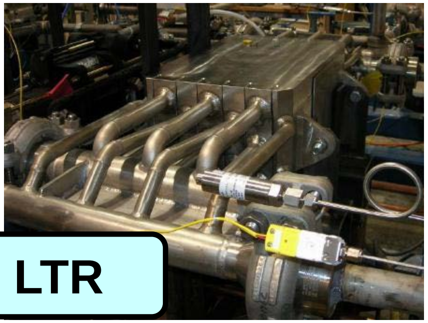


Goal:
1/10th the cost
1/100th the volume
Of conventional
steam Rankine

Current SCO2 CBC HXers

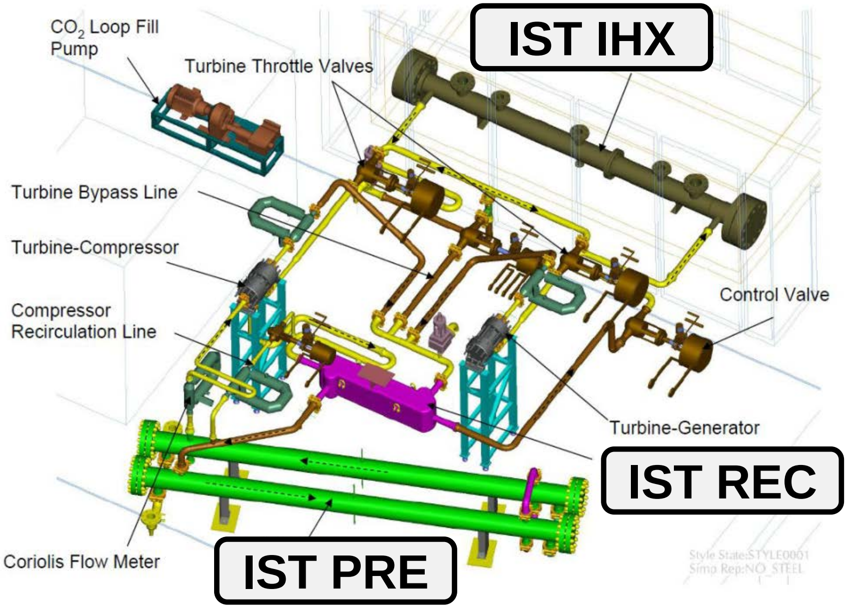


SNL HTR



SNL LTR

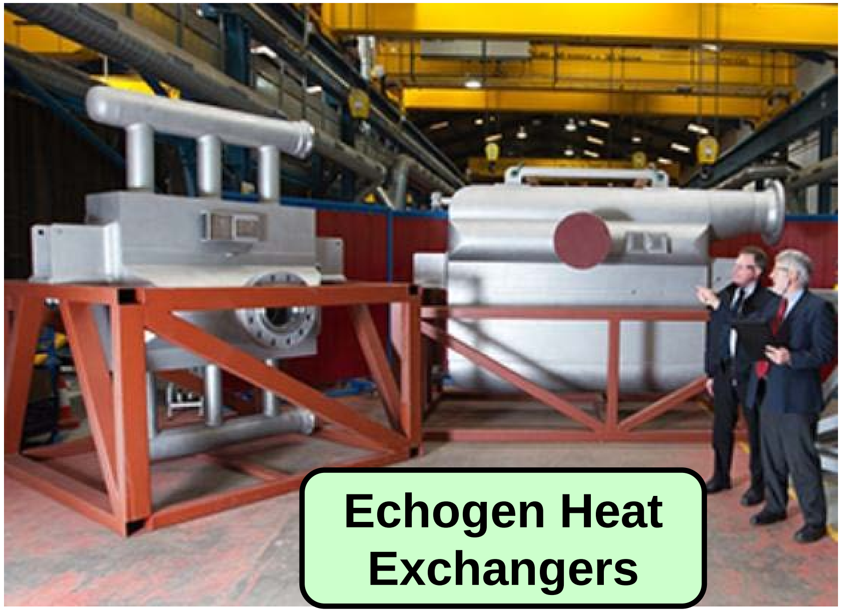
SNL PRE



IST IHX

IST REC

IST PRE



Echogen Heat Exchangers

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

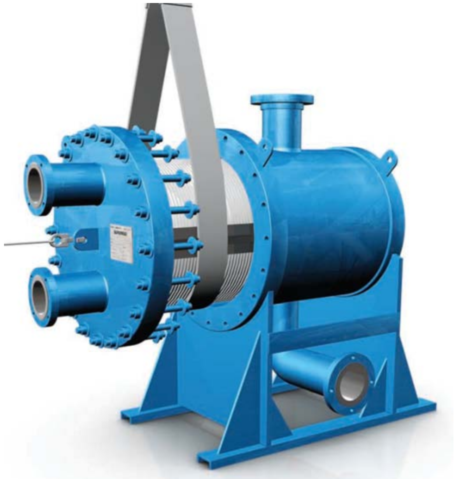
$$\beta = \frac{A_s}{V} = \frac{4\phi}{d_h}$$

Coil-Wound
10 to 300 [m^2/m^3]

Shell and Tube
10 to 200 [m^2/m^3]

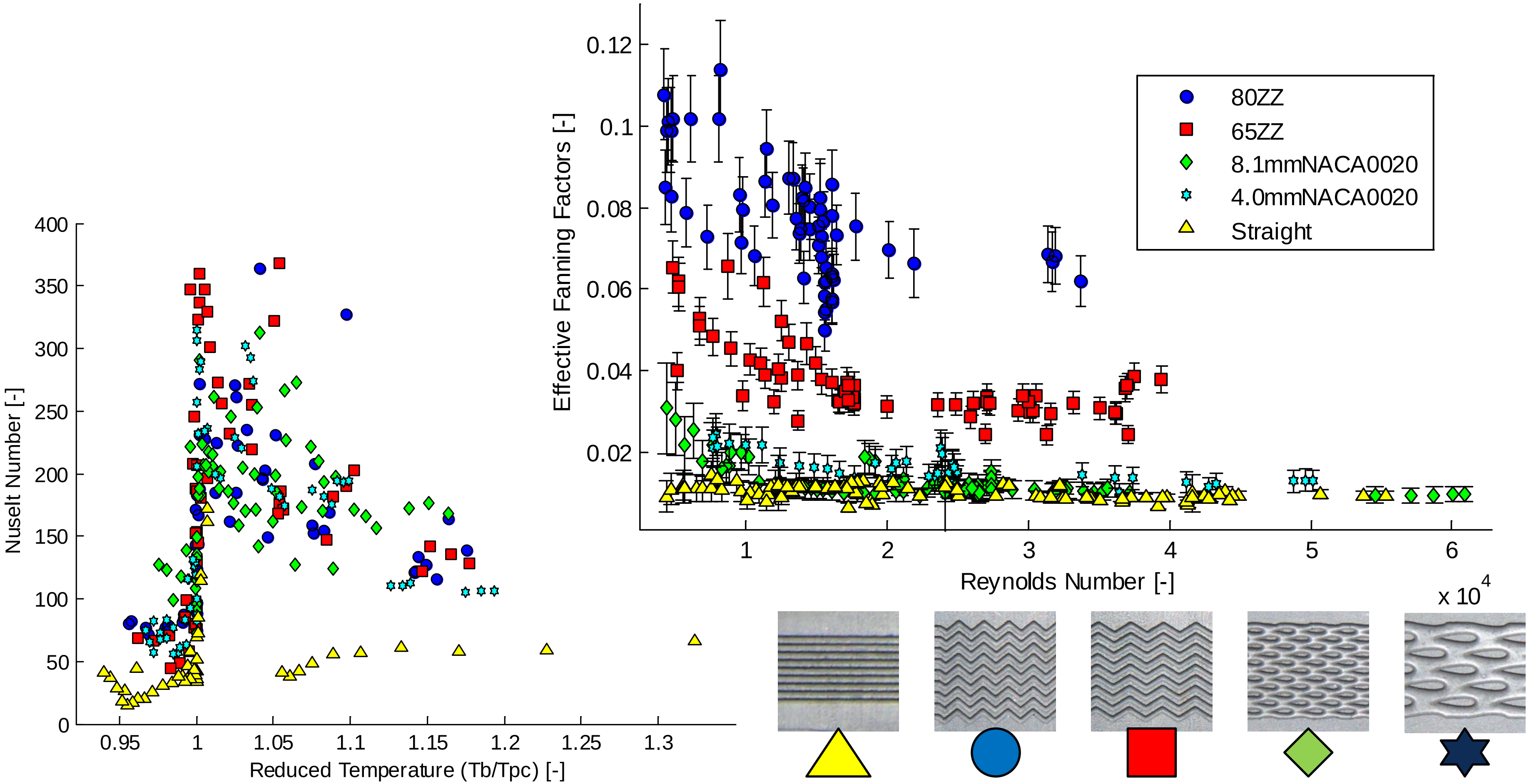
Plate-Fin
200 to 800 [m^2/m^3]

Printed Circuit
200 to 5000 [m^2/m^3]

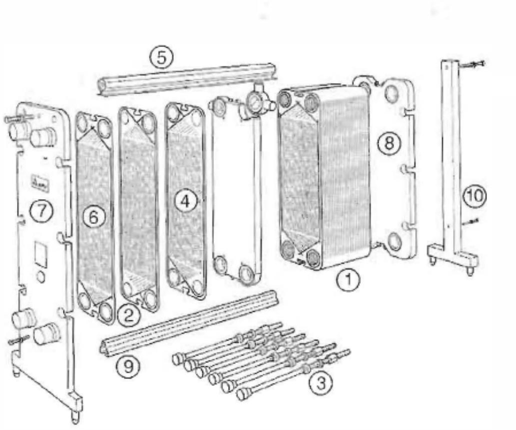


Shell and Plate
100 to 600 [m^2/m^3]

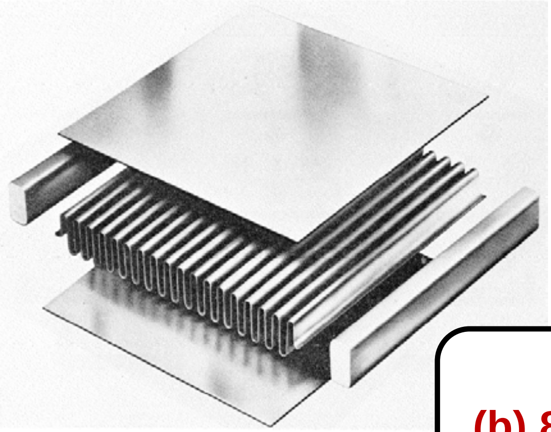
PCHE Thermal-Hydraulic Performance



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.

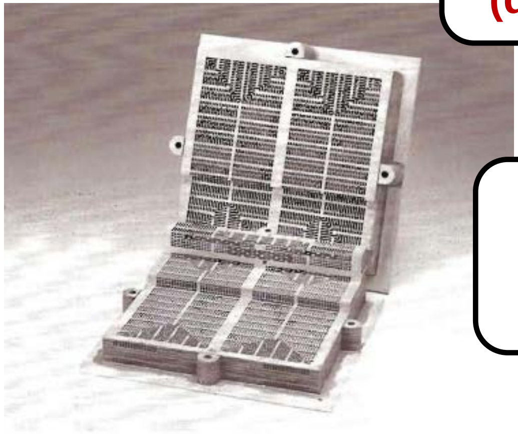


PHE
120 to 660



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

PCHE
(d) 200 to 5000



CBHE
(Marbond)
Up to 10000

HEAT EXCHANGER COMPACTNESS

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

Potential Applications

Coal / Nuclear

Steam Rankine

MARINE

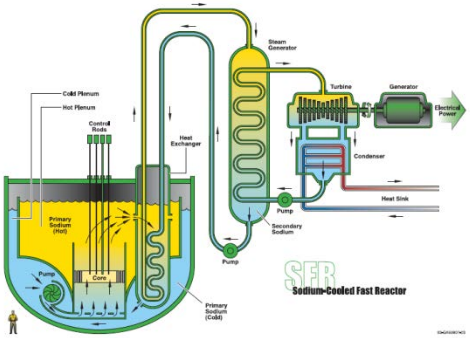
Rolls-Royce WR-21

Type 45 Destroyer

VEHICULAR

Honeywell AGT1500

M1 Abrams Tank

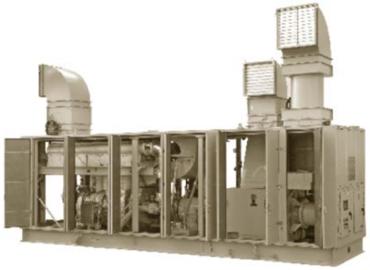


GenIV Nuclear

Sodium Fast Reactor

Refrigeration

Commercial, Cryogenic

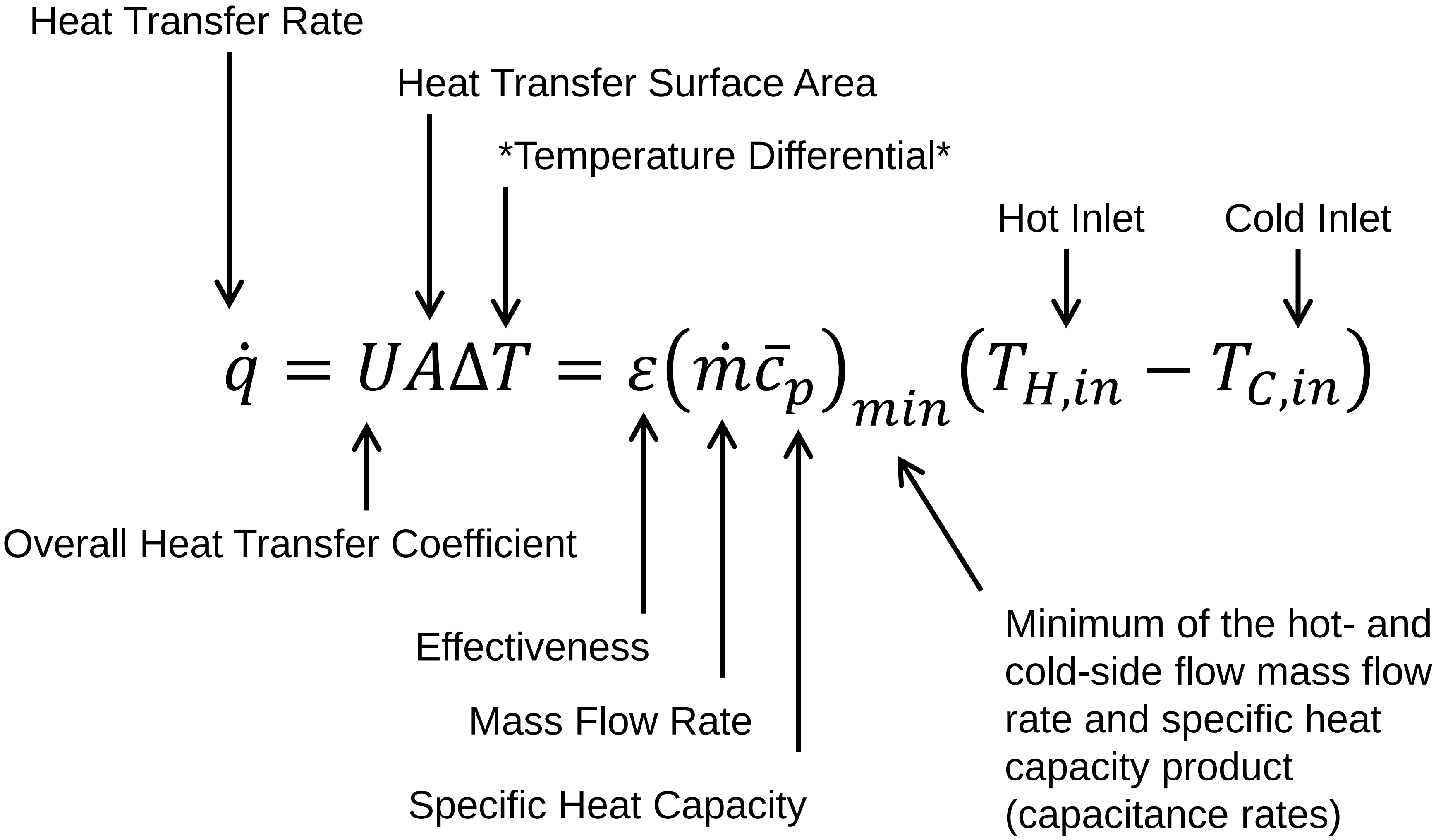


STATIONARY

Solar Turbines

Mercury 50

Effectiveness and Scaling Behavior



Heat Transfer Rate

Heat Transfer Surface Area

Temperature Differential

Hot Inlet

Cold Inlet

$$\dot{q} = UA\Delta T = \varepsilon\left(\dot{m}\bar{c}_p\right)_{min}\left(T_{H,in} - T_{C,in}\right)$$

Overall Heat Transfer Coefficient

Effectiveness

Mass Flow Rate

Specific Heat Capacity

Minimum of the hot- and cold-side flow mass flow rate and specific heat capacity product (capacitance rates)

Fundamental Scaling Behavior

Heat Transfer Rate

Heat Transfer Surface Area

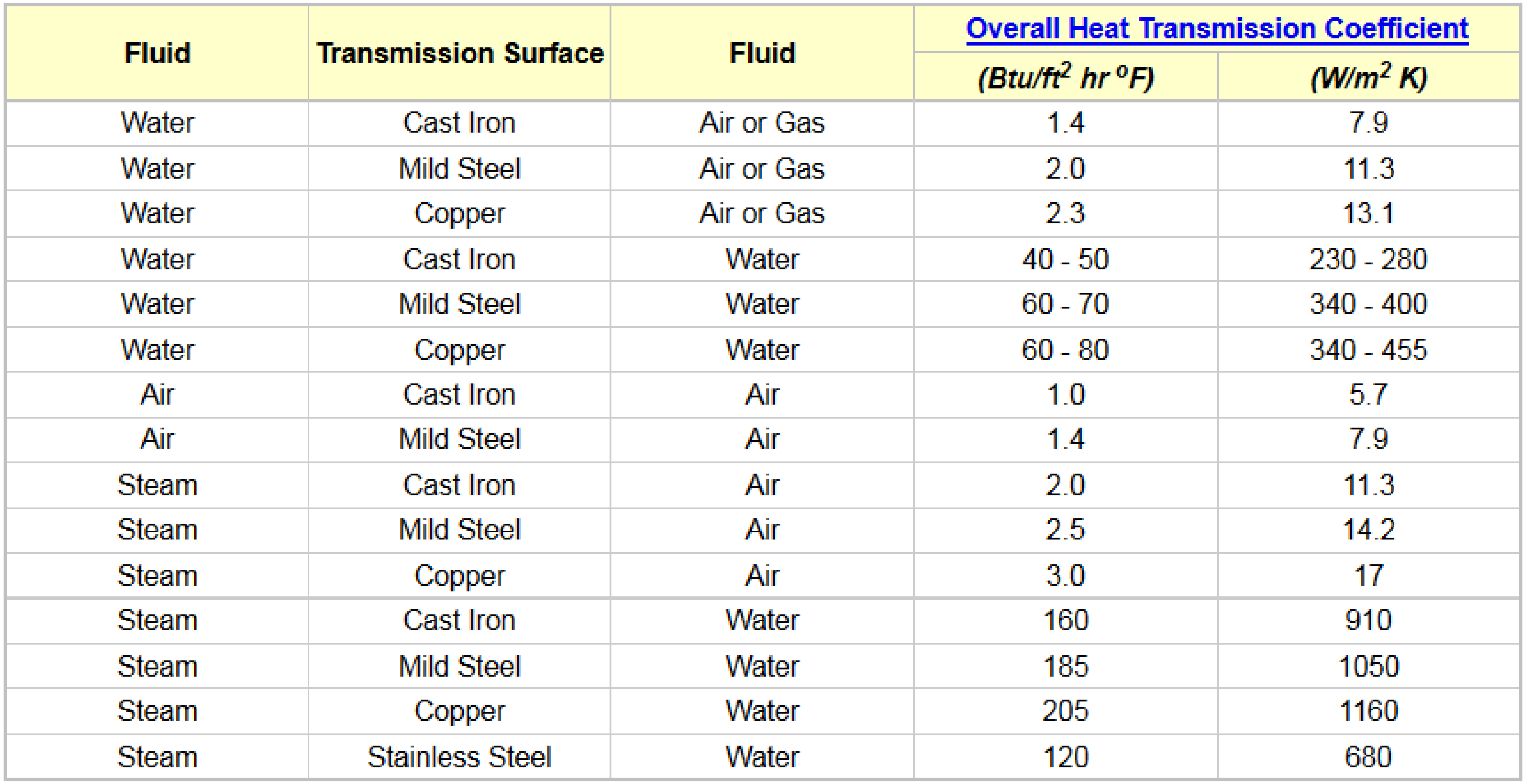
Temperature Differential

$$\dot{q} = UA\Delta T$$

Overall Heat Transfer Coefficient

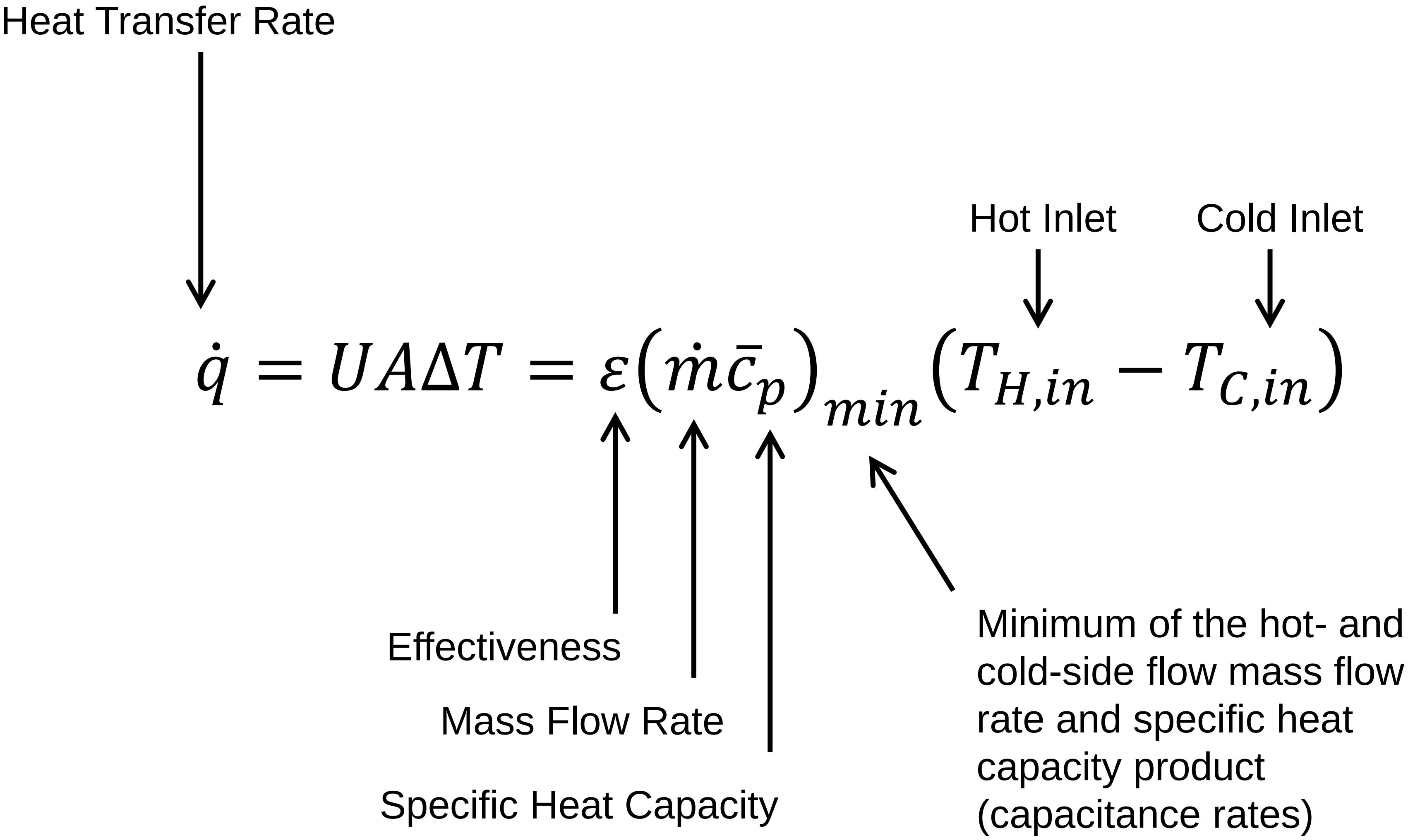
Fundamental Scaling Behavior

$$\dot{q} = UA\Delta T$$



Fluid	Transmission Surface	Fluid	Overall Heat Transmission Coefficient	
			$(Btu/ft^2\ hr\ ^oF)$	$(W/m^2\ K)$
Water	Cast Iron	Air or Gas	1.4	7.9
Water	Mild Steel	Air or Gas	2.0	11.3
Water	Copper	Air or Gas	2.3	13.1
Water	Cast Iron	Water	40 - 50	230 - 280
Water	Mild Steel	Water	60 - 70	340 - 400
Water	Copper	Water	60 - 80	340 - 455
Air	Cast Iron	Air	1.0	5.7
Air	Mild Steel	Air	1.4	7.9
Steam	Cast Iron	Air	2.0	11.3
Steam	Mild Steel	Air	2.5	14.2
Steam	Copper	Air	3.0	17
Steam	Cast Iron	Water	160	910
Steam	Mild Steel	Water	185	1050
Steam	Copper	Water	205	1160
Steam	Stainless Steel	Water	120	680

Effectiveness and Scaling Behavior



Heat Transfer Rate

Hot Inlet

Cold Inlet

$$\dot{q} = UA\Delta T = \varepsilon\left(\dot{m}\bar{c}_p\right)_{min}\left(T_{H,in} - T_{C,in}\right)$$

Effectiveness

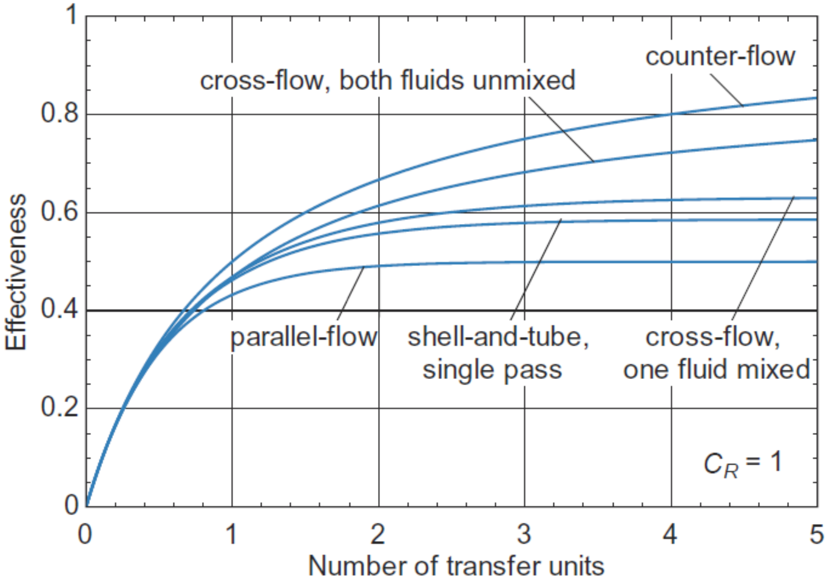
Mass Flow Rate

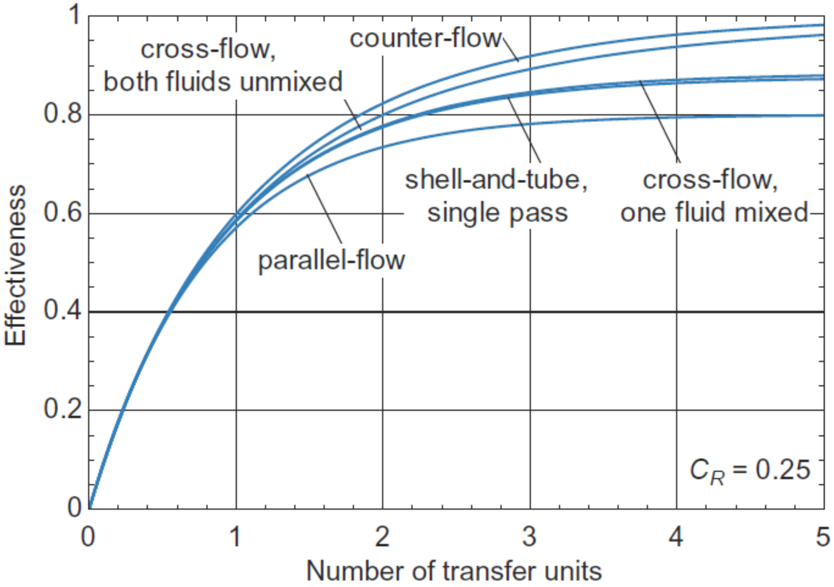
Specific Heat Capacity

Minimum of the hot- and cold-side flow mass flow rate and specific heat capacity product (capacitance rates)

Other Useful e-NTU Scaling

- Configuration matters most for $C_R = 1$; counter-flow is best
- Effectiveness is asymptotic with NTU (size); 1 for counter-flow
- Configuration matters less as C_R approaches 0





$C_R = 1$

$C_R = 0.25$

Pressure Drop Correlations

$$\Delta P = \sum \Delta P_{friction} + \sum \Delta P_{local} + \sum \Delta P_{acceleration} + \sum \Delta P_{body\ forces}$$

- Body Forces

$$\Delta P_{gravity} = g\left(\frac{i_{out}\,\rho_{out} + i_{in}\rho_{in}}{i_{out} + i_{in}}\right) Lsin(\theta)$$

- Local Form Losses

$$\frac{\Delta P_{local}}{G^2/2\rho} = K_{loss} = f\left(\frac{L_{equivalent}}{d_{hyd}}\right)$$

- Acceleration Difference

$$\Delta P_{acceleration} = G^2\left(\frac{1}{\rho_{out}} - \frac{1}{\rho_{in}}\right)$$

$$\Delta P_{friction} = f\frac{L_s}{d_{hyd}}\frac{1}{2}\frac{G^2}{\rho}$$

Blasius → Kondrat'ev

$$f = 0.316Re^{-0.25} \quad \rightarrow \quad f = 0.188Re^{-0.22}$$

Haaland → Filonenko

$$f = \frac{1}{\left(1.8\log_{10}\left[\left(\frac{RR}{3.7}\right)^{1.11} + \frac{6.9}{Re}\right]\right)^2} \quad \rightarrow \quad f = \frac{1}{(1.82\log_{10} Re_b - 1.64)^2}$$

Colebrook Equation

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{RR}{3.7} + \frac{2.51}{Re\sqrt{f}}\right)$$

Heat Transfer Correlations

Constant Property

Supercritical Fluids

Dittus-Boelter Correlation

$$Nu = C\ Re^{n}\, Pr^{m}$$

→

Jackson’s Correlation

$$Nu = 0.0183 Re_b^{0.82} Pr_b^{0.5} \left(\frac{\rho_w}{\rho_b}\right)^{0.3} \left(\frac{\bar{c}_p}{c_{p,b}}\right)^{n}$$

Gnielinski Correlation

$$Nu = \frac{\left(\frac{f}{8}\right)(Re - 1000)Pr}{1 + 12.7\sqrt{\frac{f}{8}}\left(Pr^{\frac{2}{3}} - 1\right)}$$

→

Pitla Correlation

$$Nu = \left(\frac{Nu_w|_{Gnielinski} + Nu_b|_{Gnielinski}}{2}\right)\frac{k_w}{k_b}$$