SAND2017-12725PE

State of Art in PCHE Development and Associated Research at Sandia

sCO2 Summit

November 14-15, 2017, Albuquerque, NM, USA

Matthew D. Carlson

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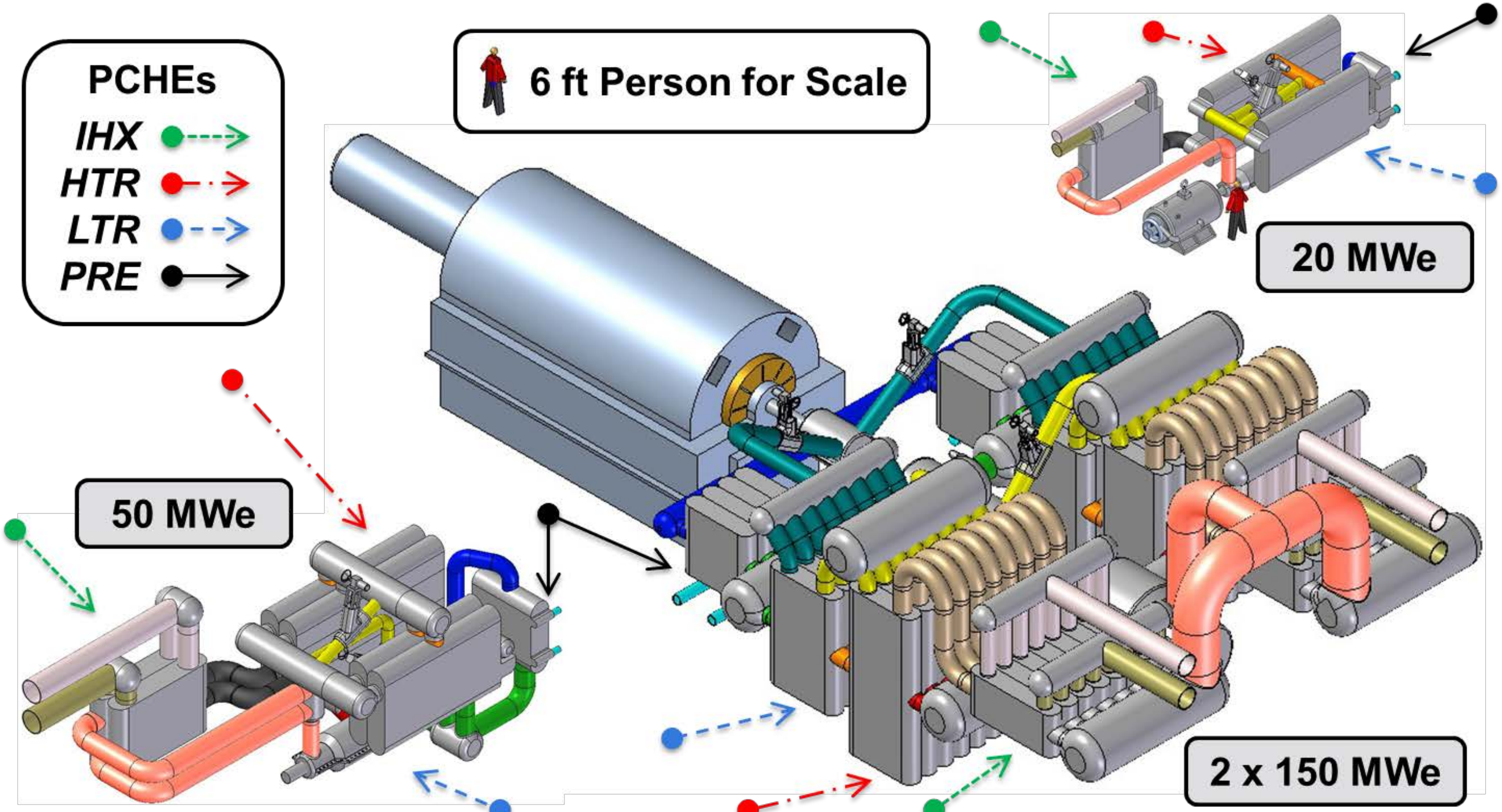
HEAT EXCHANGER STATE OF THE ART

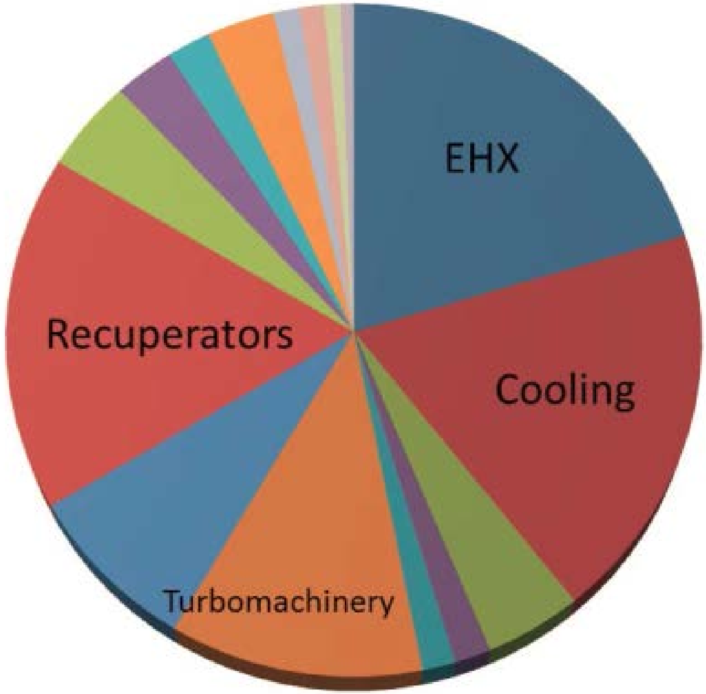
Heat Exchangers are Critical for sCO2



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.

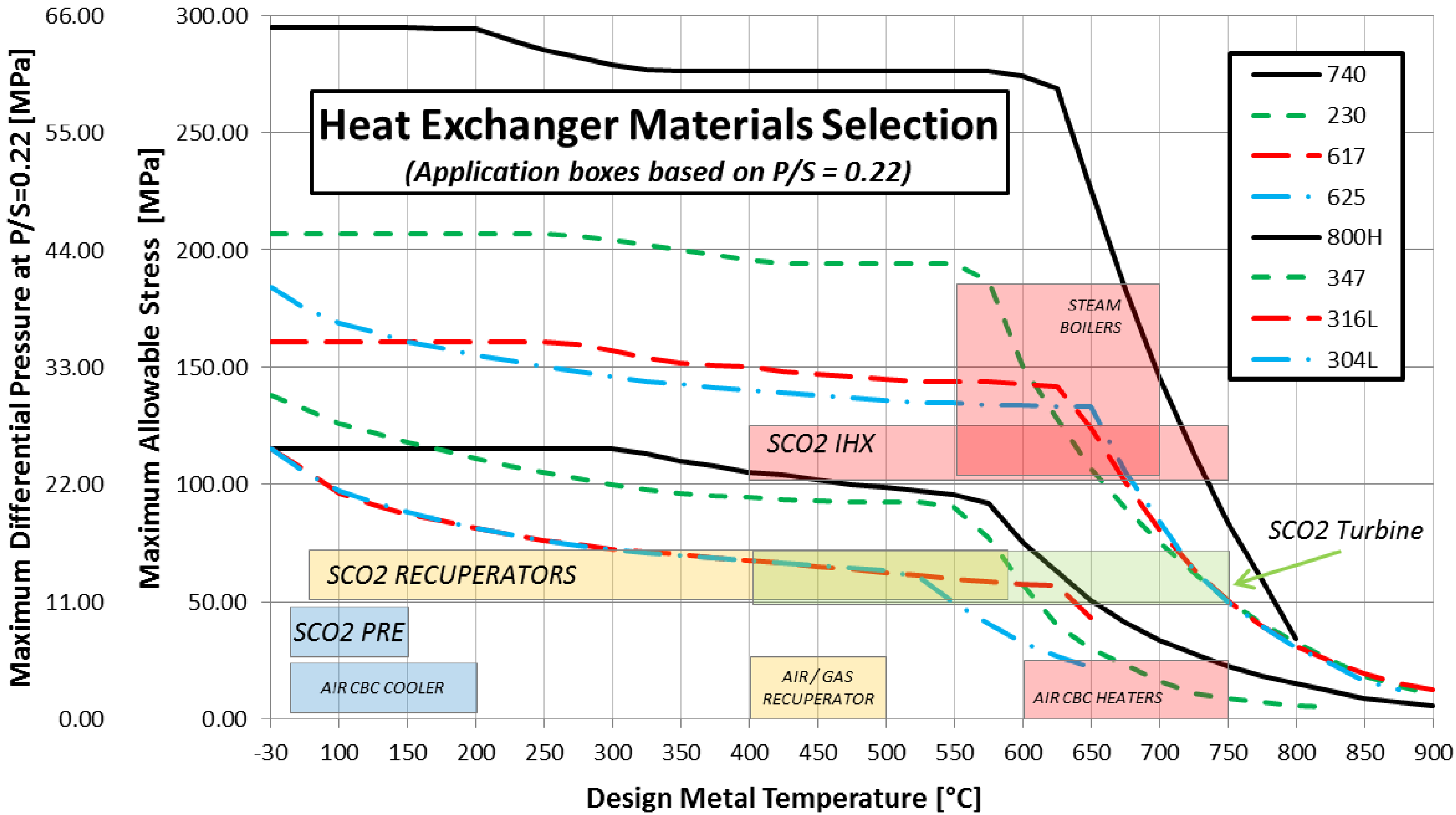
Heat Exchangers are a Major Cost

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

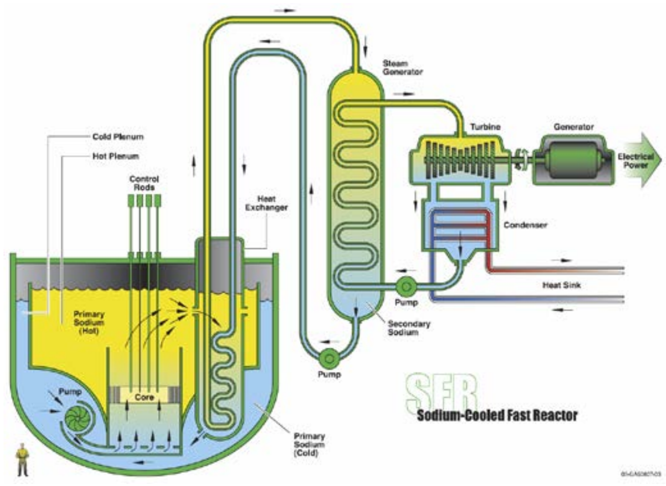


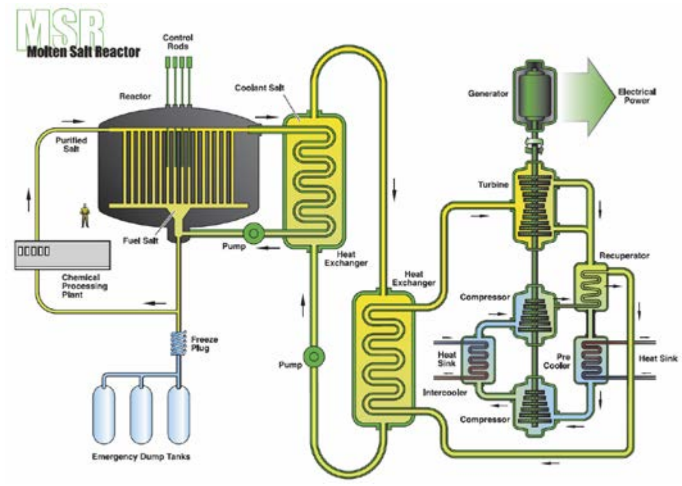
T. Held, “Performance & cost targets for sCO2 heat exchangers,” presented at the National Energy Technology Laboratory - EPRI Workshop on Heat Exchangers for Supercritical CO2 Power Cycles, San Diego, CA, USA, 15-Oct-2015.

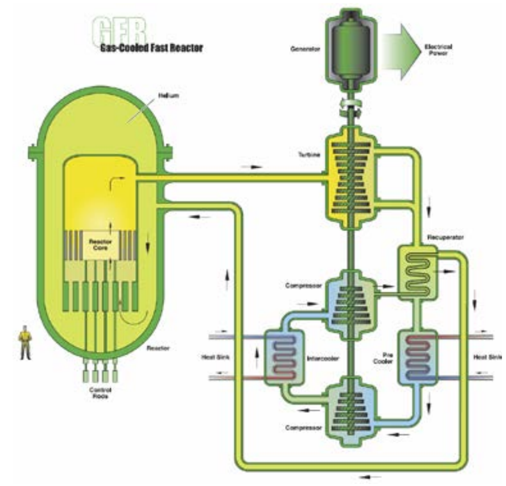
Heat Exchangers push Materials



Nuclear Power Pathway Exchangers







Sodium Fast Reactor	Molten Salt Reactor	Gas Fast Reactor
Sodium/Sodium HXer	**Salt/Salt HXer**	**(N/A)**
High reliability, tritium	*High reliability, tritium*	*N/A*
Sodium/sCO2 HXer	**Salt/sCO2 HXer**	**Helium/sCO2 HXer**
Tritium, high pressure	*Tritium, high pressure*	*High pressure*
sCO2 Recuperator		
sCO2 Water Cooler		
High sCO2-side temperature and pressure, corrosion, size/cost		

Solar Power Pathway Exchangers

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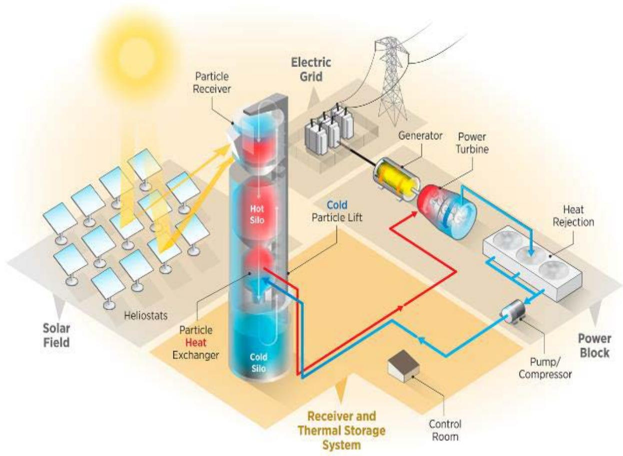
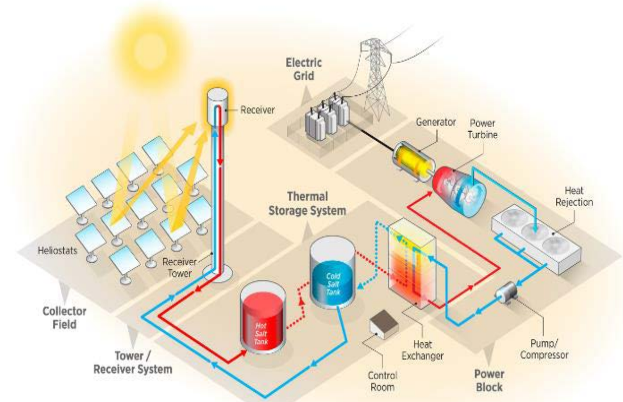
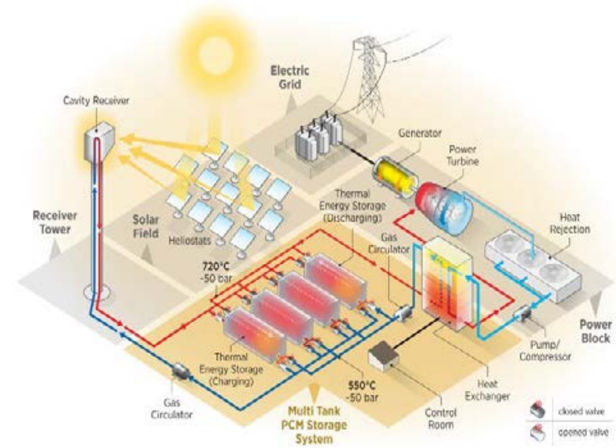
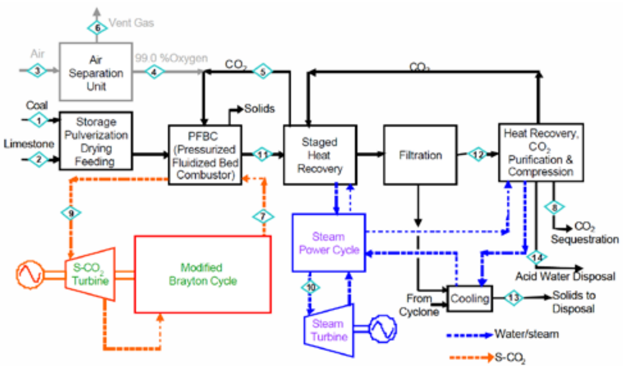




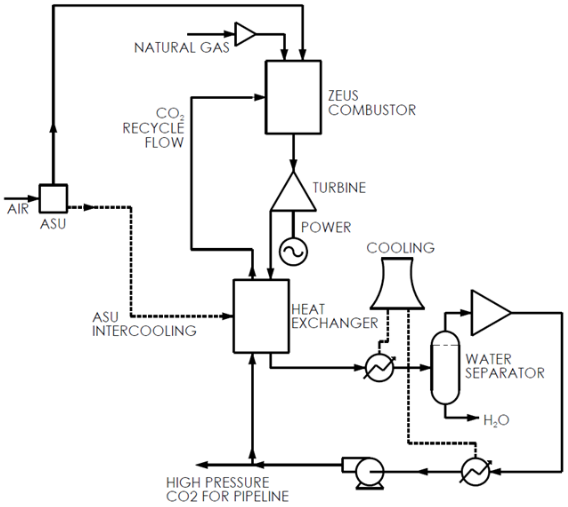


Solid (particles)	Liquid (salt)	Gas (+ storage)
Particle Receiver	**Molten Salt Receiver**	**Gas Receiver**
Efficiency	*Corrosion, cycling*	*Cycling*
Particle/sCO2 HXer	**Molten Salt/sCO2 HXer**	***Storage/sCO2 Hxer**
Erosion, size/cost, cycling	*Corrosion, size/cost, cycling*	*Size/cost, cycling*
sCO2 Recuperator		
sCO2 Air Cooler		
High sCO2-side temperature and pressure, corrosion, size/cost		

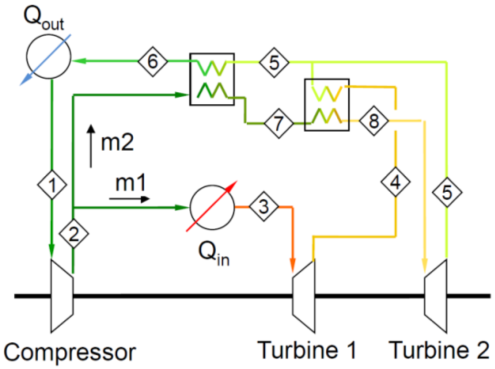
Fossil Power Pathway Exchangers



ZEPS™



Allam et al.



Kimzey

Coal (direct)	Natural Gas (direct)	Bottoming Cycle
Combustor	**Combustor**	**Waste Heat Exchanger**
High CO2 combustion	*High CO2 combustion*	*High temperature/pressure*
sCO2 Recuperator	**sCO2 Recuperator**	**sCO2 Recuperator**
Combustion products, T/P	*Combustion products, T/P*	*High temperature/pressure*
sCO2 Air Cooler		
High sCO2-side temperature and pressure, corrosion, size/cost		

Configuration Development Gaps

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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							

Exhaust Gas · Molten Salts · Liquid Metals · Fluidized Beds · High Temperature Recuperators

Key Research Areas

- Lifetime validation of compact heat exchangers
  - Failure modes
  - Pressure/thermal/corrosion-assisted fatigue
  - Creep behavior and lifetime
  - Inspection and monitoring
- Affordable compact heat exchanger configurations
  - Configurations with large (gas/liquid) and small (sCO2) flow areas
  - Fabrication using advanced corrosion-resistant materials (nickels)
  - Tritium management for nuclear applications
- Methods to leverage low-cost materials at high temperature
  - Corrosion-resistant coatings for stainless steels
  - Coating failure potential and lifetime
  - Modular designs to allow for shorter lifetimes

SUMMARY OF SANDIA RESEARCH EFFORTS

Project Map – Nuclear Applications

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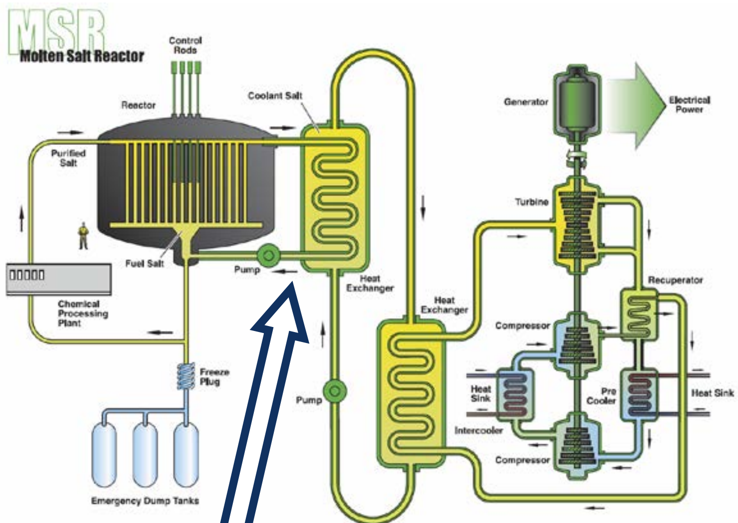
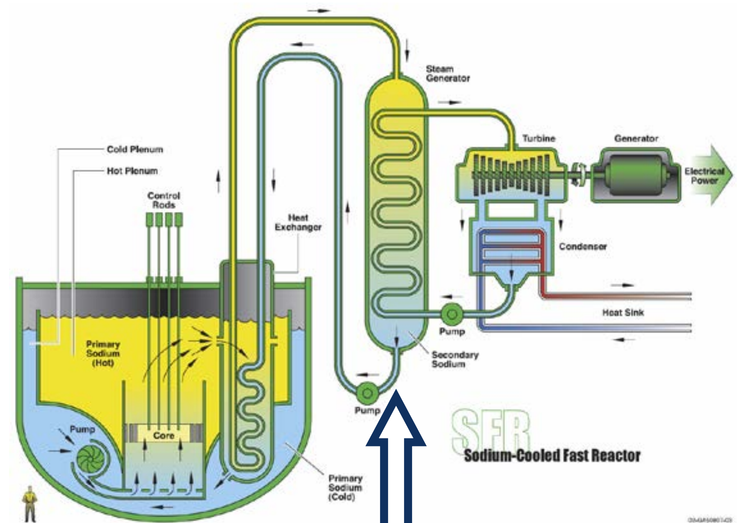
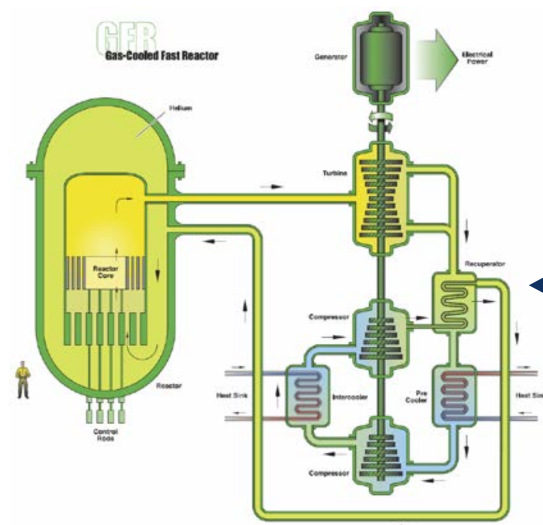






UNM NEUP
CFA-15-8667
Double-Walled
Twisted Tube HXers

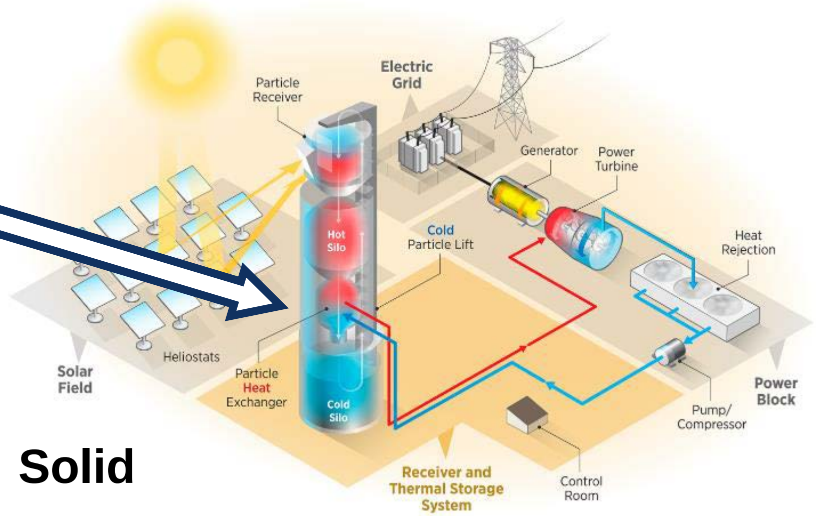
UW-Madison IRP
IRP-17-14227
Compact HXers for
Nuclear Applications

UW-Madison NEUP
CFA-17-12481
sCO2-cooled
Space Reactor

GA-Tech NEUP
CFA-16-10578
ASME-III Qualification
of Diffusion Bonding

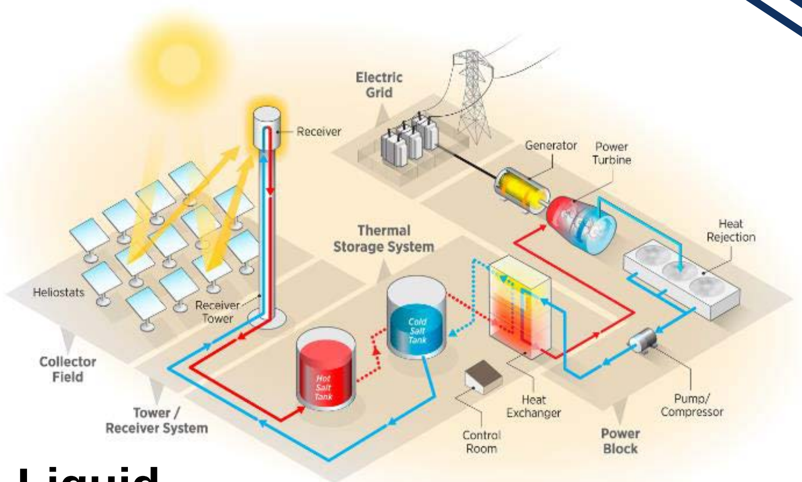
Project Map – Solar Applications

SuNLaMP
1507
Particle-sCO2 HXer

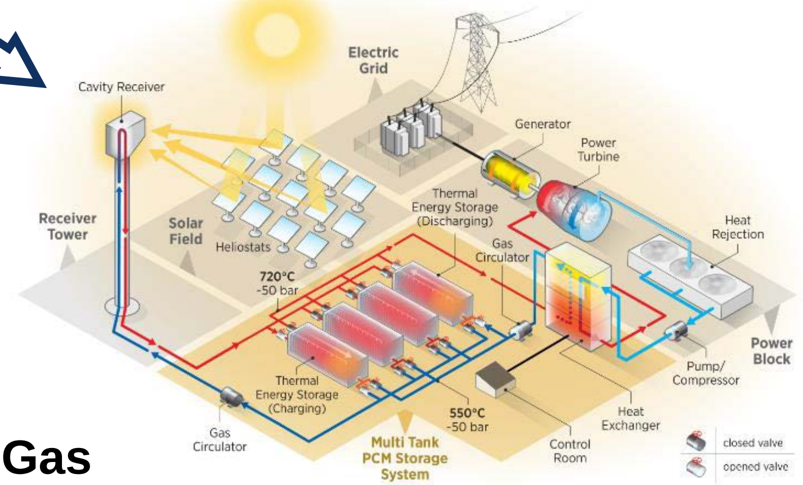


Solid

Oregon State University
DE-EE0007108
Direct sCO2 Gas Receiver



Liquid



Gas

Project Map – sCO2 Cycle Level

VPE CRADA
1822.01
Design, Shims, Headers, Lifetime

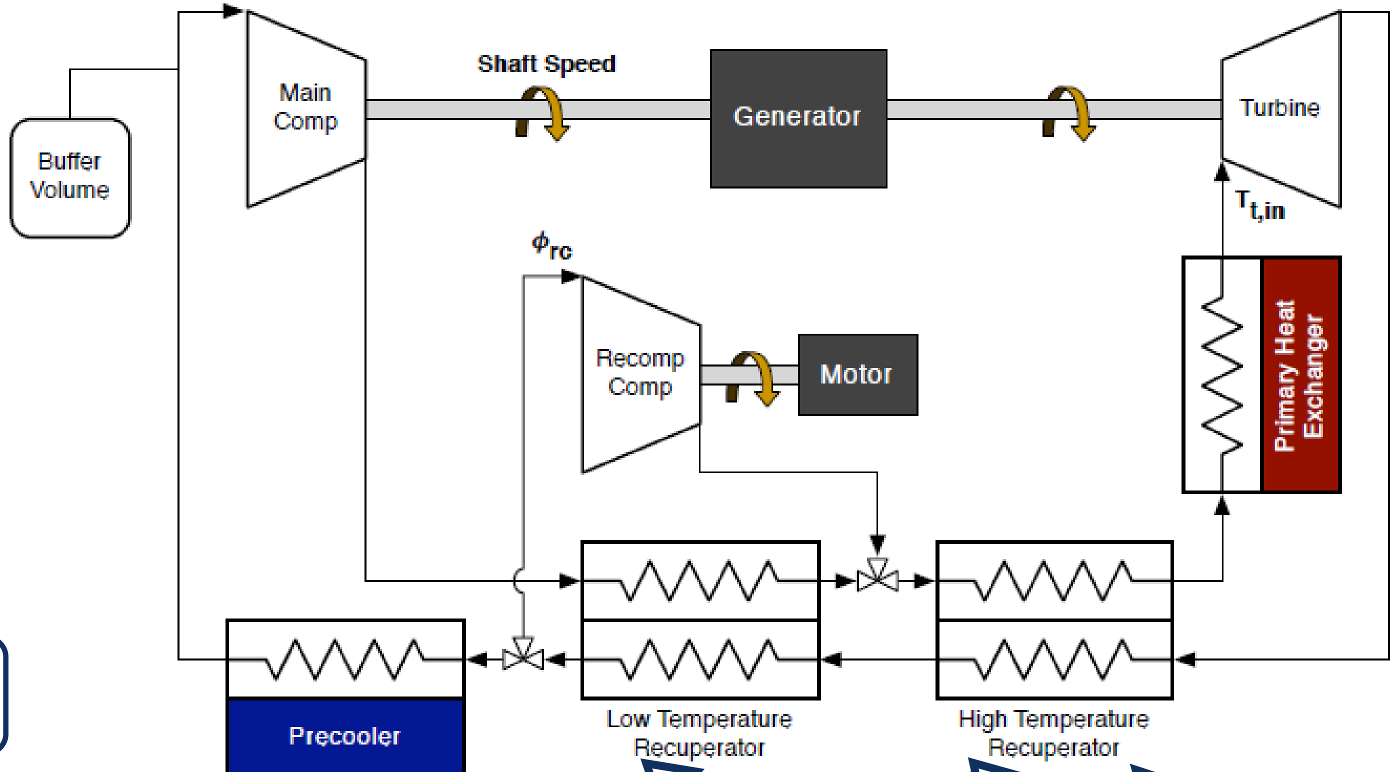
STEP 03
2.04.19.06
Cost & Lifetime

Comprex SBIR
FY17 P1R2
Large-shim Diffusion Bonding

Technology Comm. Fund
TCF-17-13556
Optimized Headers

Small-Business Voucher
EERE-0999-1766
Screen-printed Shims

HPC4Manufacturing
Proposed
SEARCH Enhancements



APOLLO
DE-EE0001720
Switch-bed Regenerators

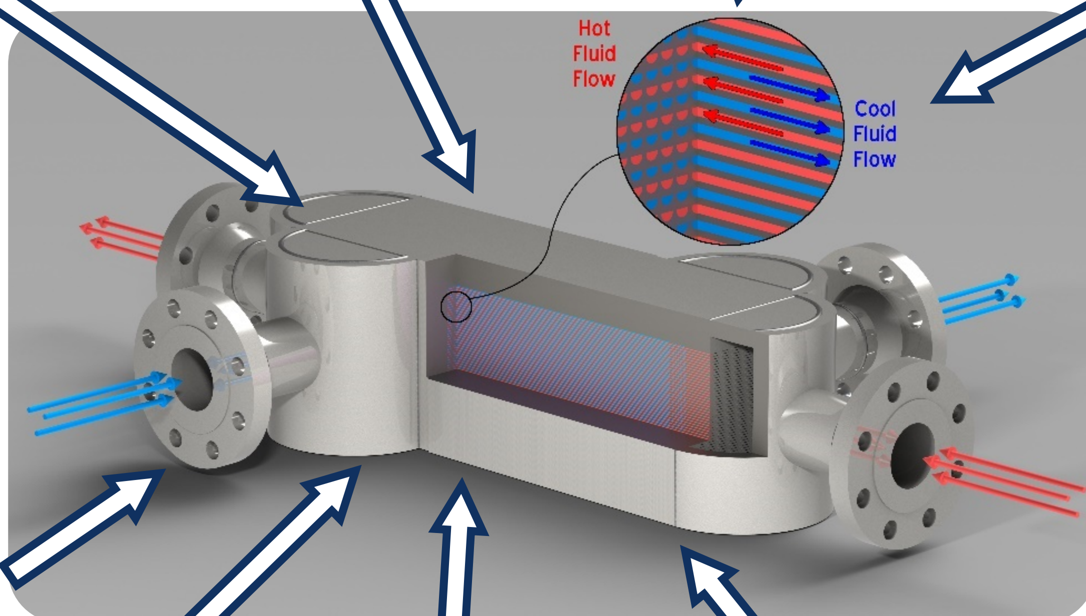
Project Map – Component Level

Comprex SBIR
FY17 P1R2
Large-shim
Diffusion Bonding

STEP 03 - Lifetime
2.04.19.06
Failure Mode Validation

STEP 03 - Design
2.04.19.06
UUR Version of SEARCH

HPC4Manufacturing
Proposed
SEARCH Enhancements



STEP 03 - Headers
2.04.19.06
Pressure & Flow Validation

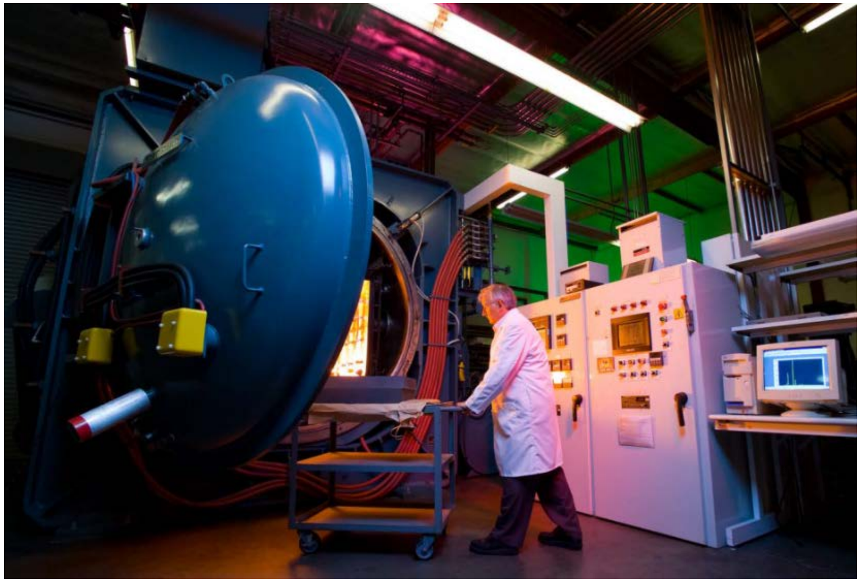
Technology Comm. Fund
TCF-17-13556
Optimized Headers

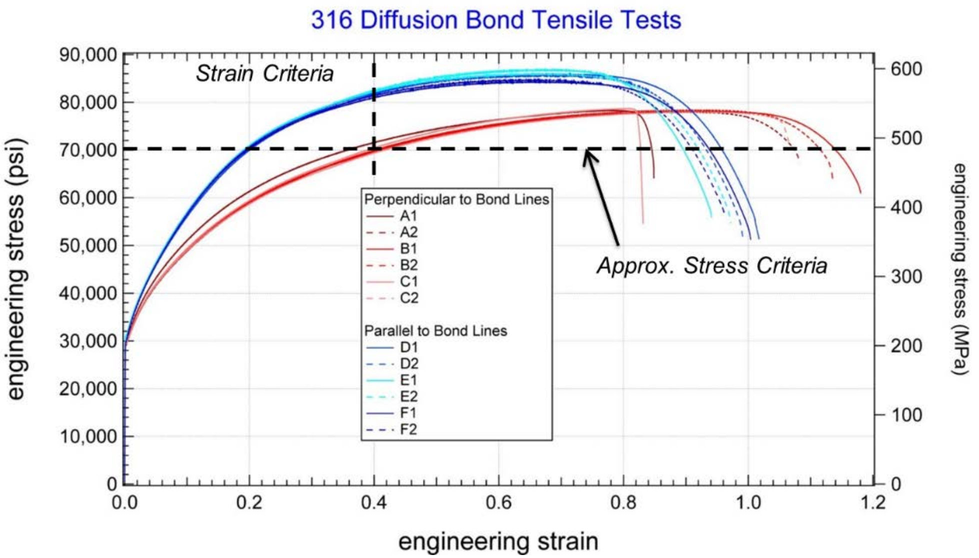
STEP 03 - Shims
2.04.19.06
Hybrid Additive
Manufacturing

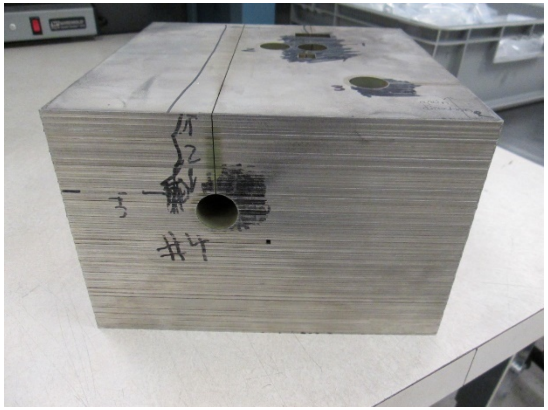
Small-Business Voucher
EERE-0999-1766
Screen-printed Shims

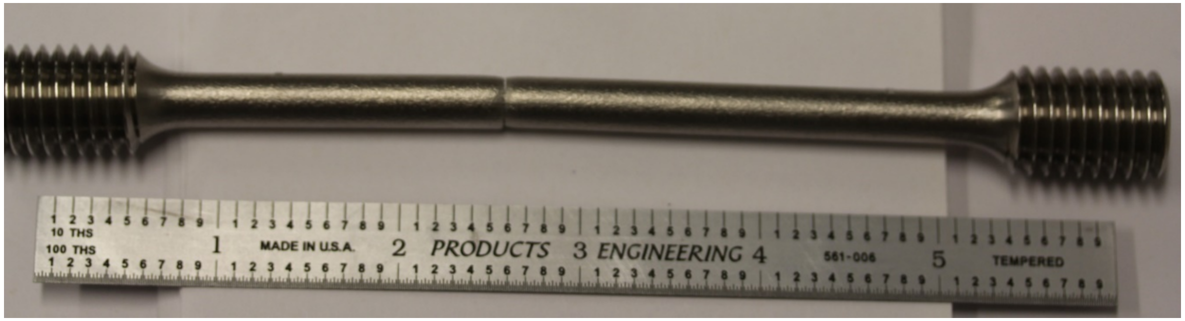
VPE CRADA
1822.01
Design, Shims,
Headers, Lifetime

VPE Bonding Process Certification









SEARCH Heat Exchanger Design Tool

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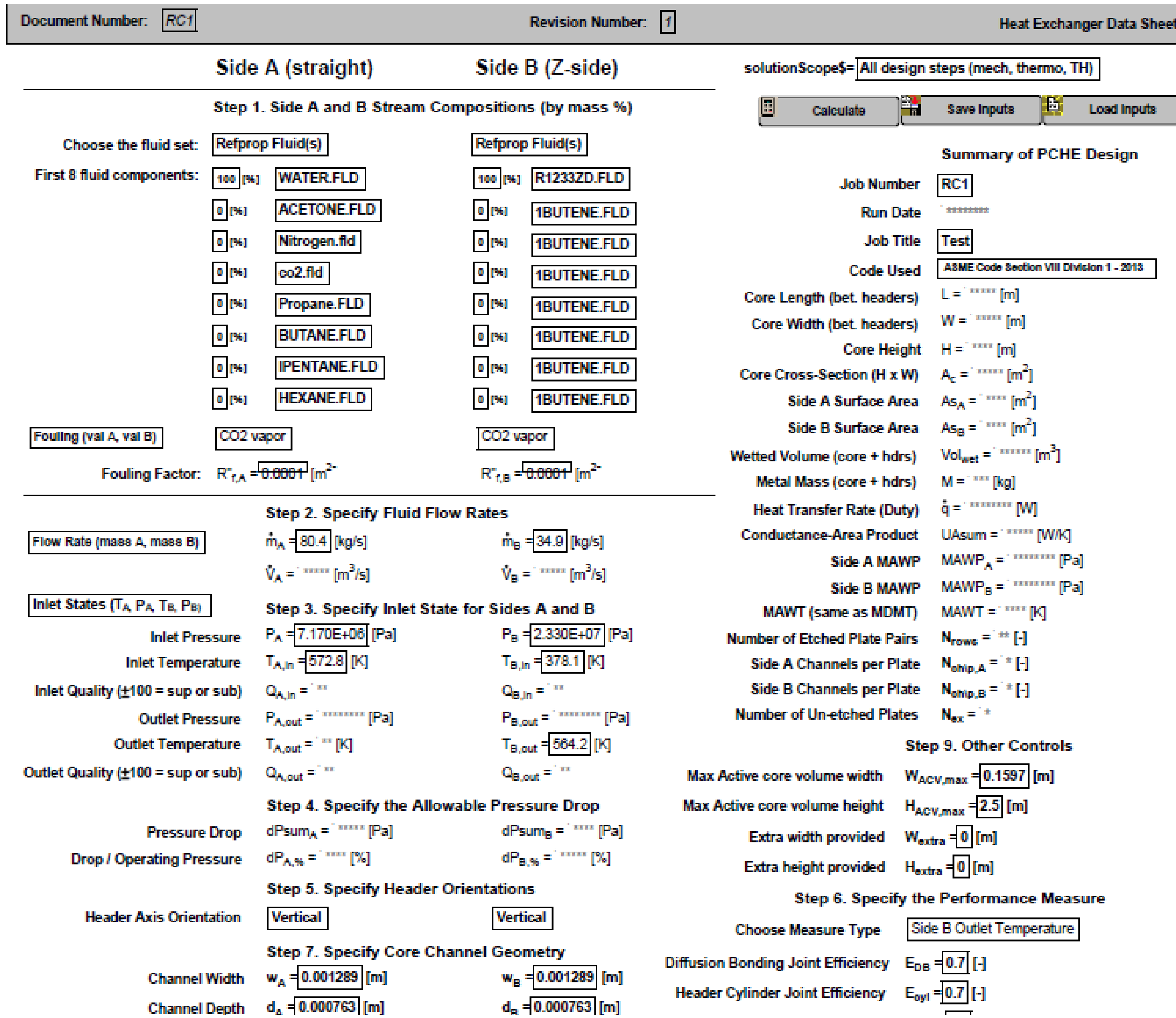
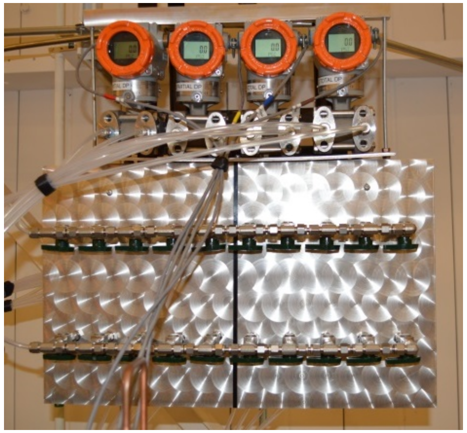
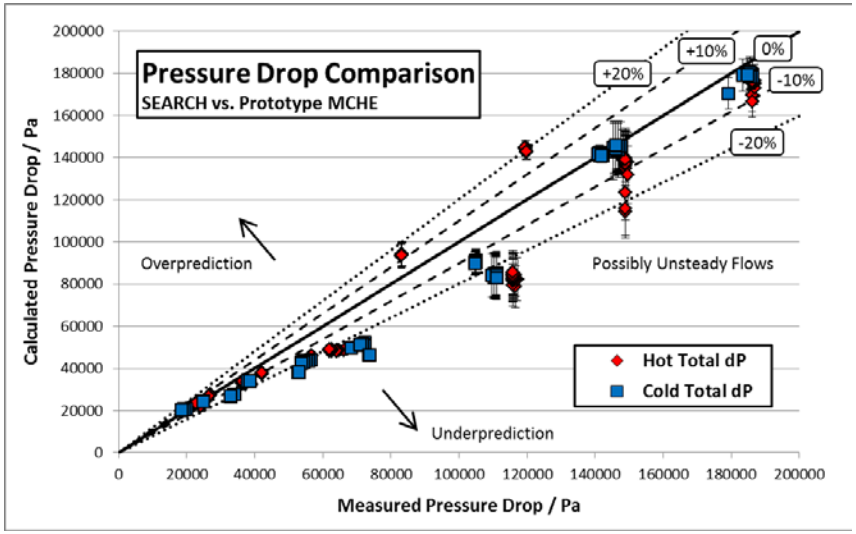
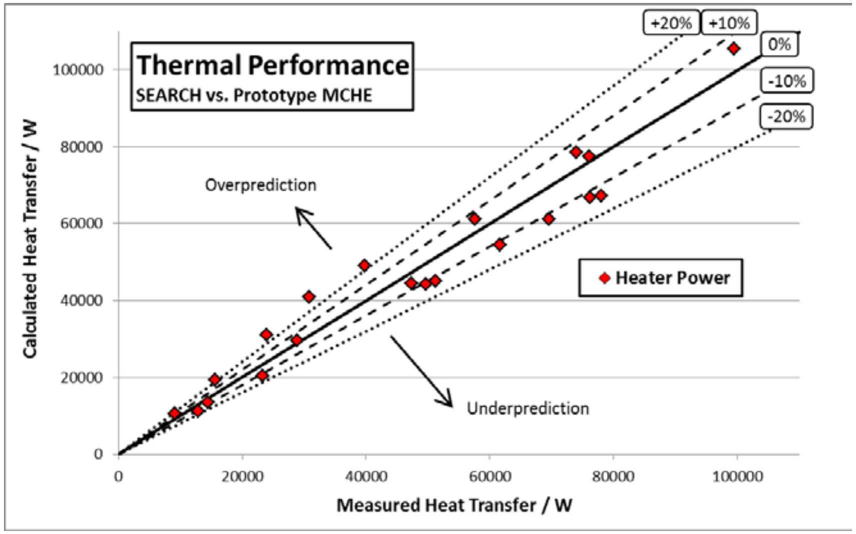
- **Sub-hxer model**
- **ASME BPVC**
- **Single, two-phase, supercritical flows**
- **Over 400 fluids**



SEARCH Experimental Verification







Design Optimization

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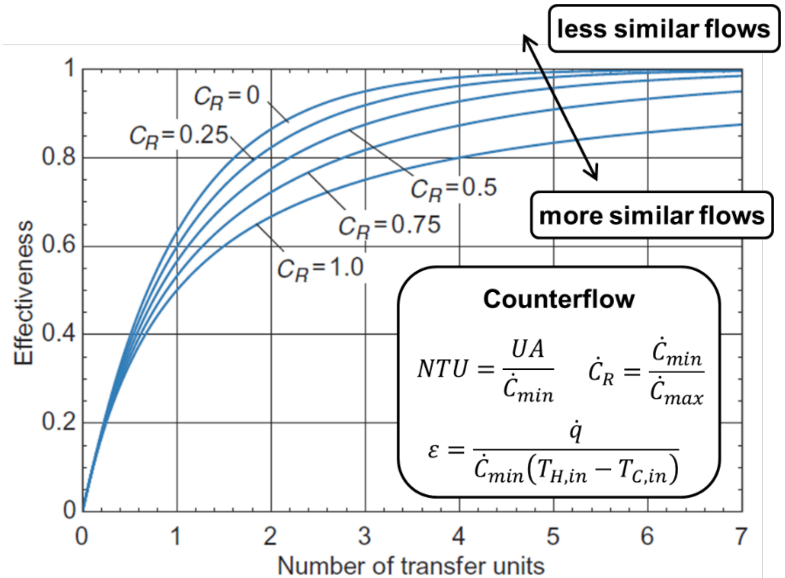
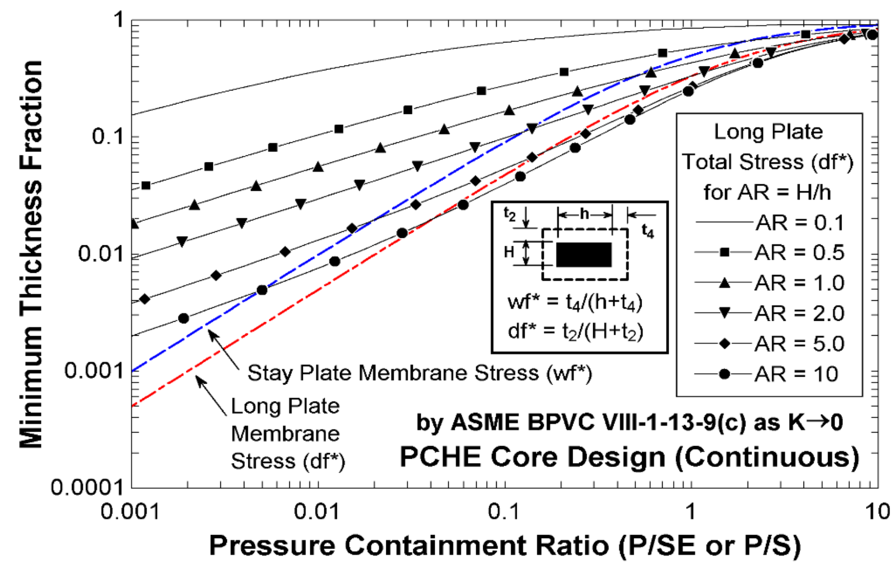


Thermodynamics



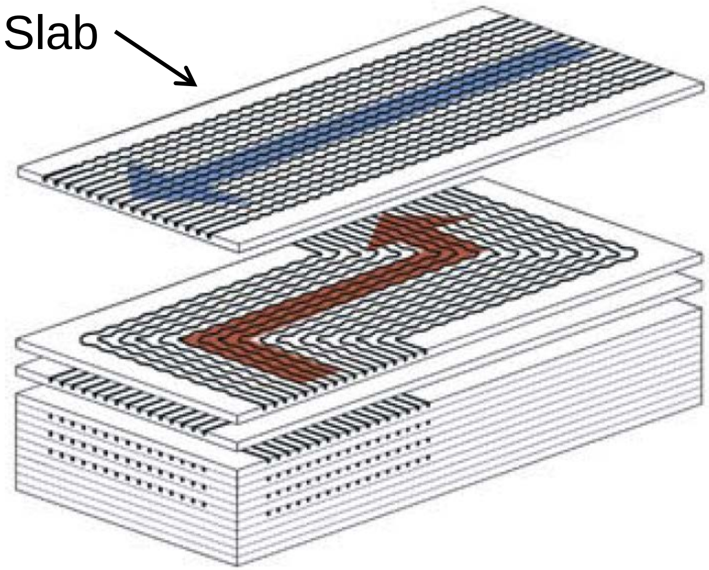
Pressure Containment

Thermal-Hydraulics

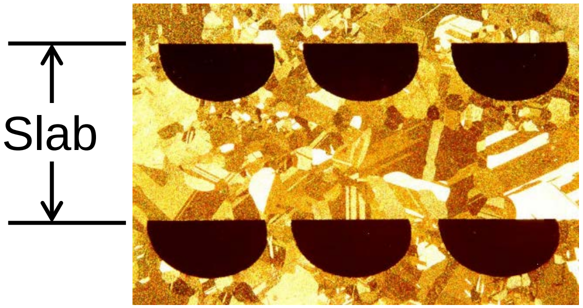
$$\Delta x_i = UA_i\left(\frac{1}{h_{A,i}N_{ch,A}p_{ch,A}} + \frac{R''_{f,A,i}}{N_{ch,A}p_{ch,A}} + \frac{t_m}{k_{m,i}W} + \frac{1}{h_{B,i}N_{ch,B}p_{ch,B}} + \frac{R''_{f,B,i}}{N_{ch,B}p_{ch,B}}\right)$$

Hybrid Additive Manufacturing

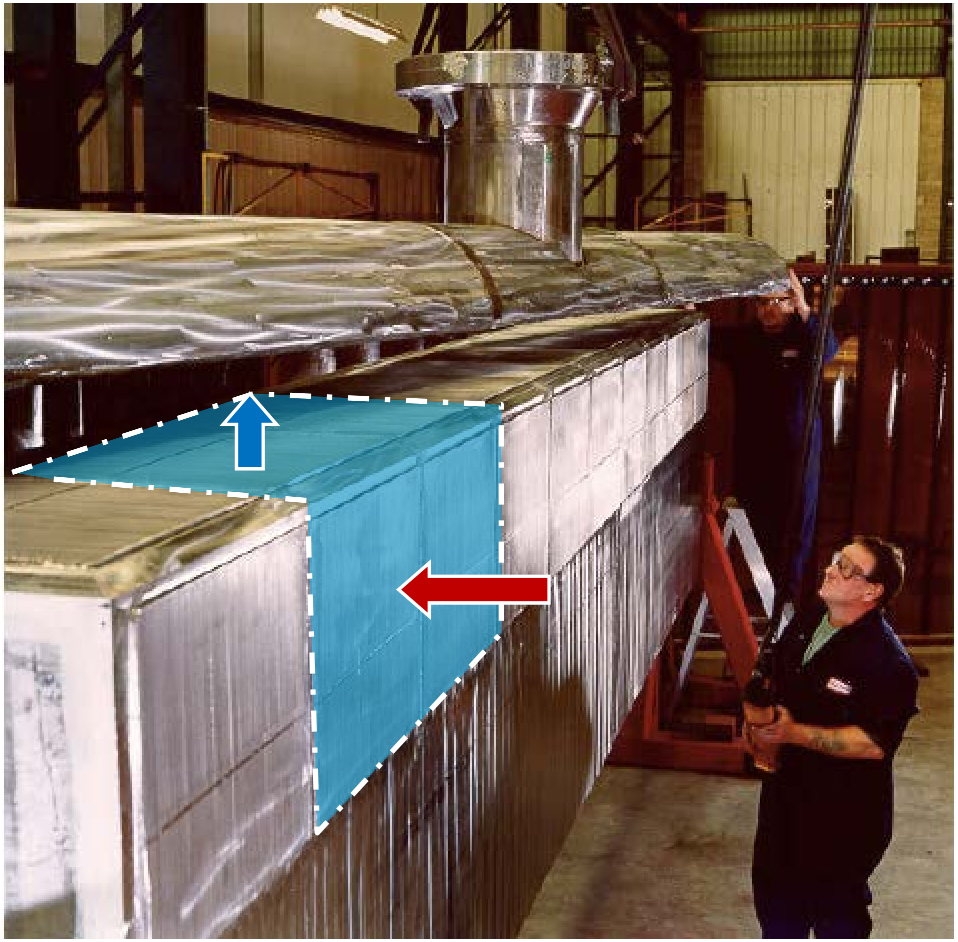
Heat Exchanger Core



Diffusion Bonding



Core and Manifold Assembly



Hybrid Additive Manufacturing

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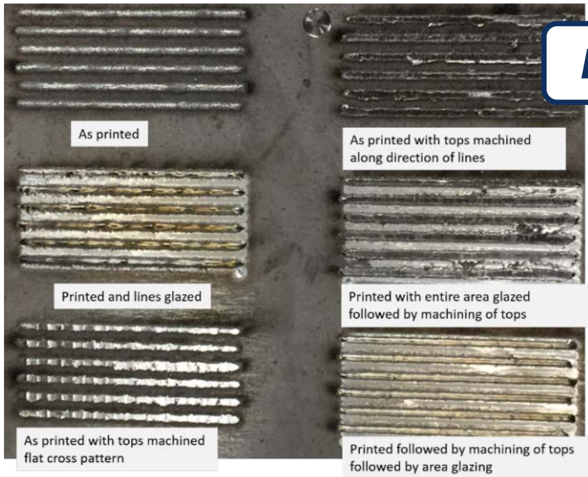
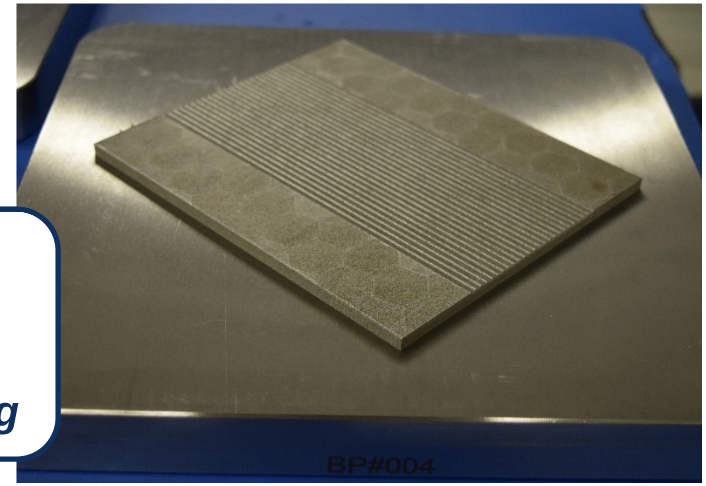
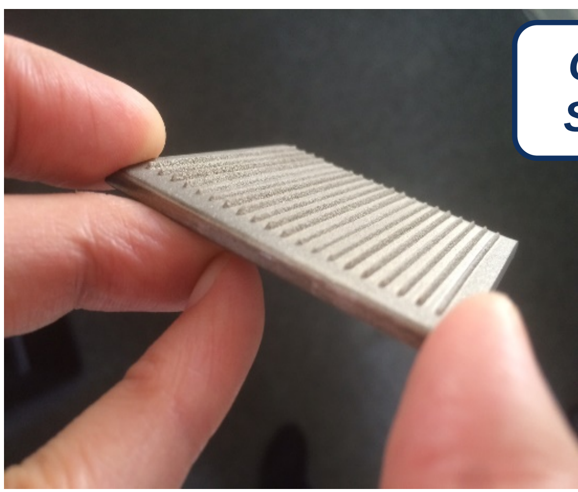


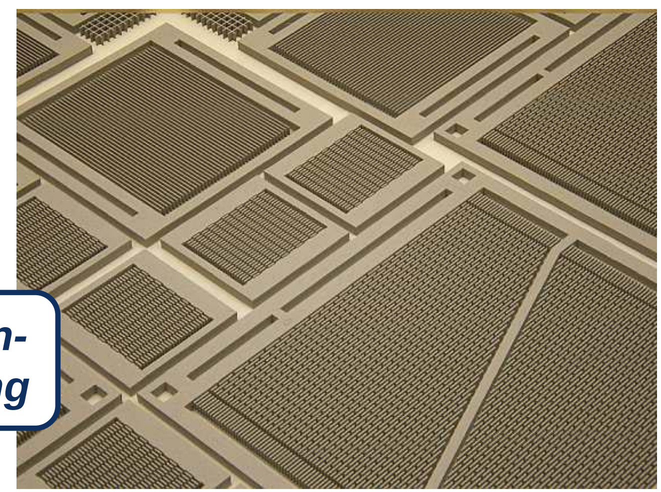
LENS



Direct Metal Laser Sintering



Cold-Spray

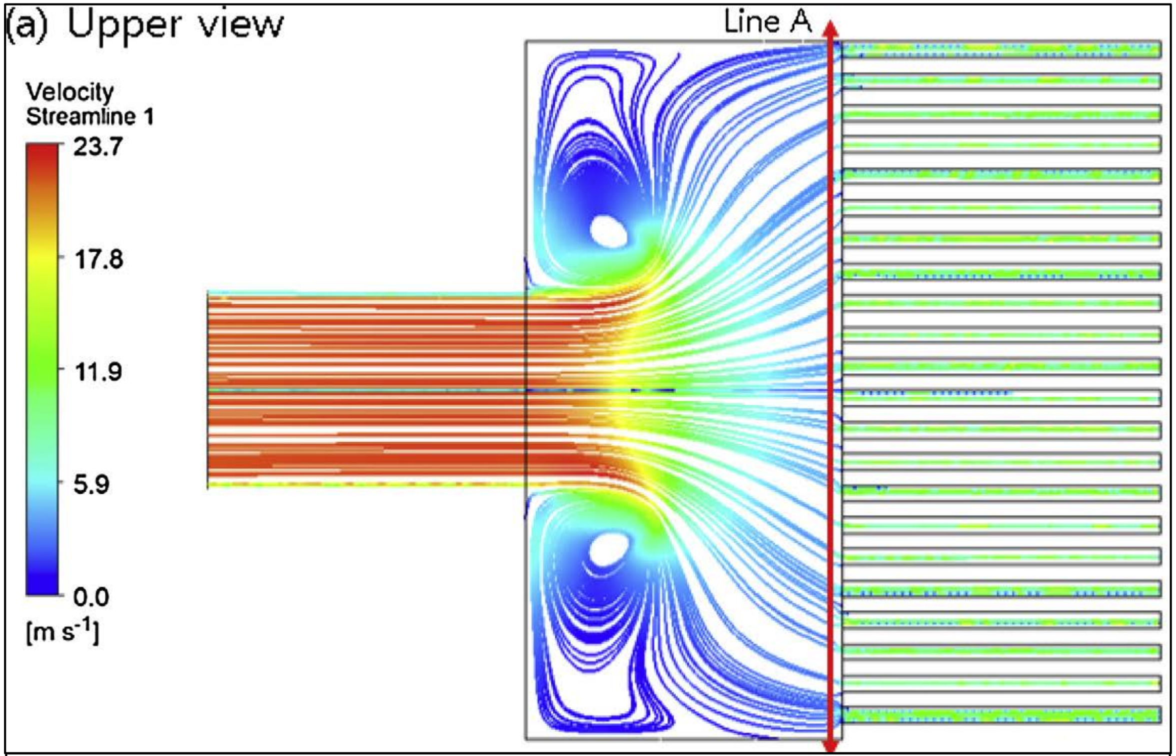


Screen-Printing

Alternative Headers:

Flow maldistribution in PCHEs reduces effectiveness

- Flow maldistribution can have a significant impact on compact heat exchanger effectiveness with reductions of 5-15%
- Others have predicted flow maldistribution with computational fluid dynamics (CFD)
- No experimental data are known for this issue

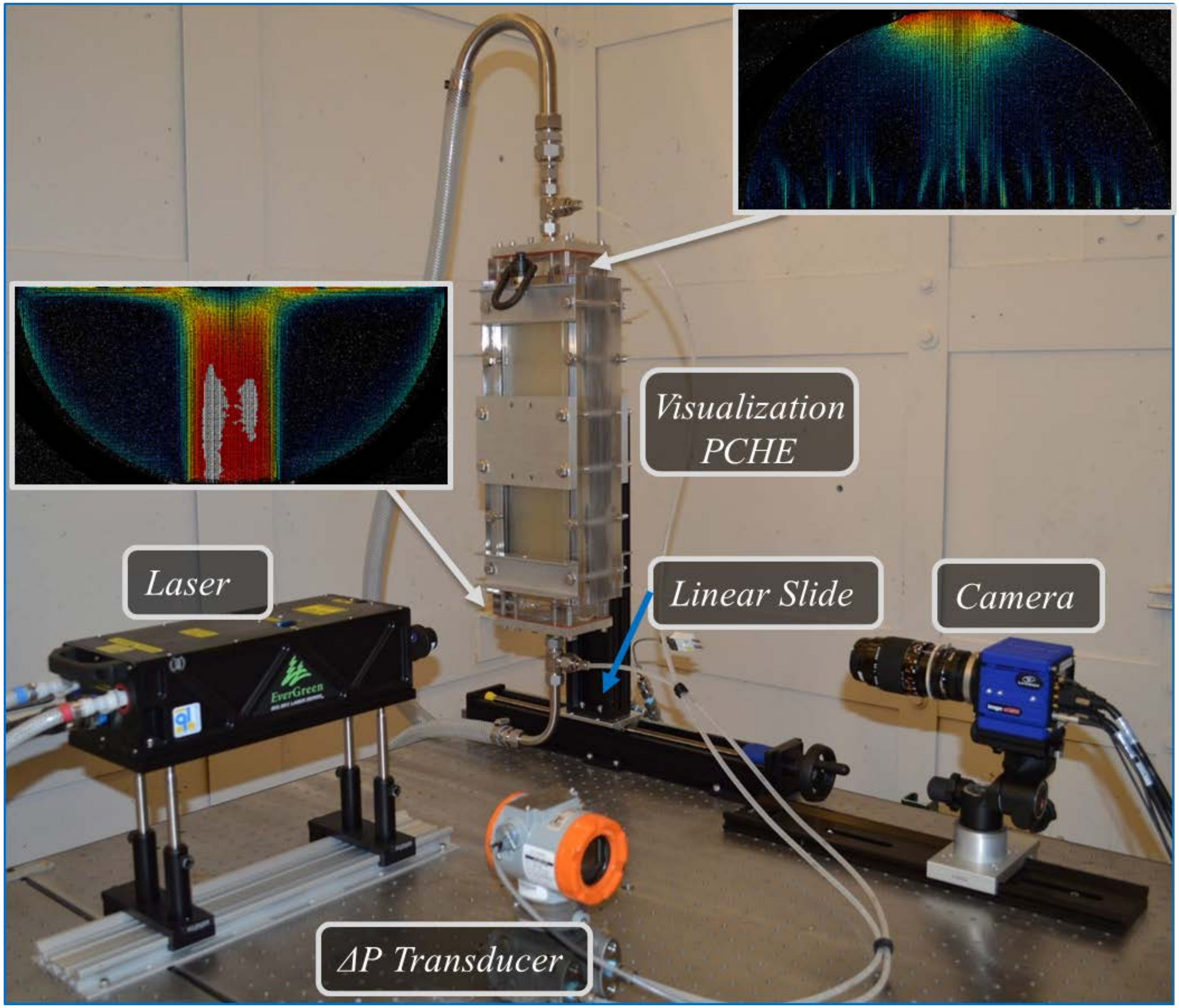


Baek, S., Lee, C., and Jeong, S., 2014, "Effect of Flow Maldistribution and Axial Conduction on Compact Microchannel Heat Exchanger," Cryogenics, 60, pp. 49-61.

Alternative Headers:

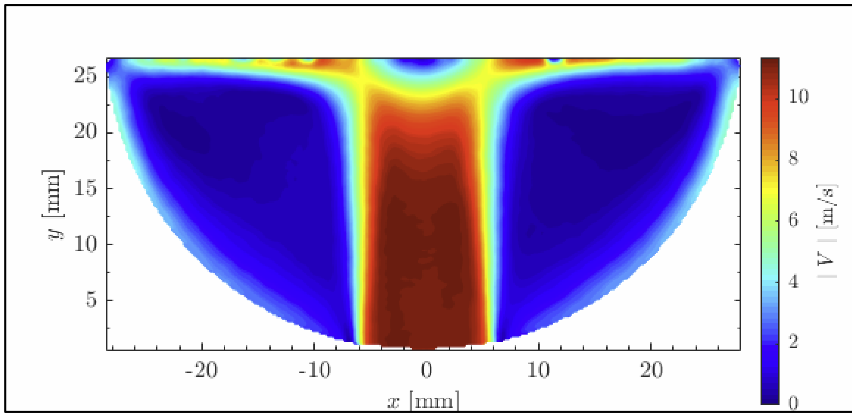
We measured the flow distribution with PIV in a PCHE prototype

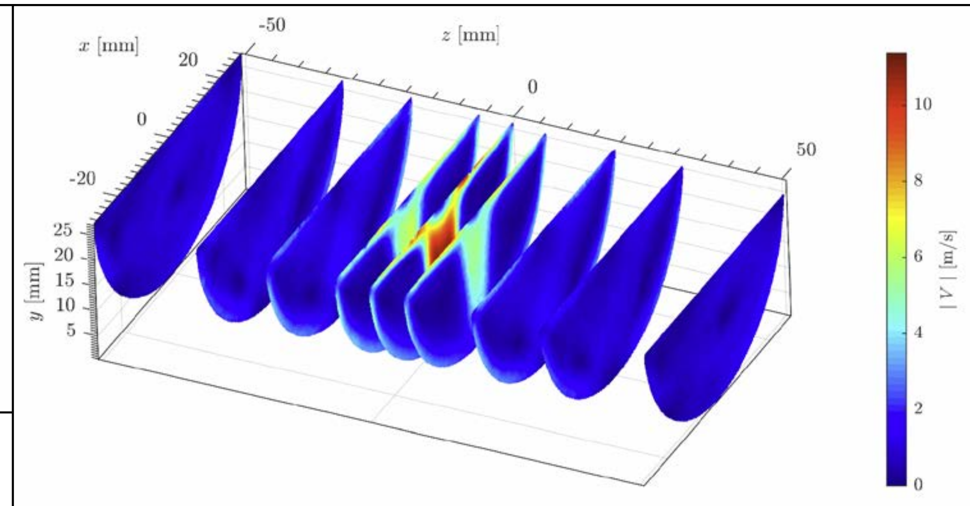
- We performed the first known measurements of flow distribution in compact heat exchangers
- An acrylic prototype was made for use with water
- An optical system called Particle Image Velocimetry (PIV) was used to measure flow fields

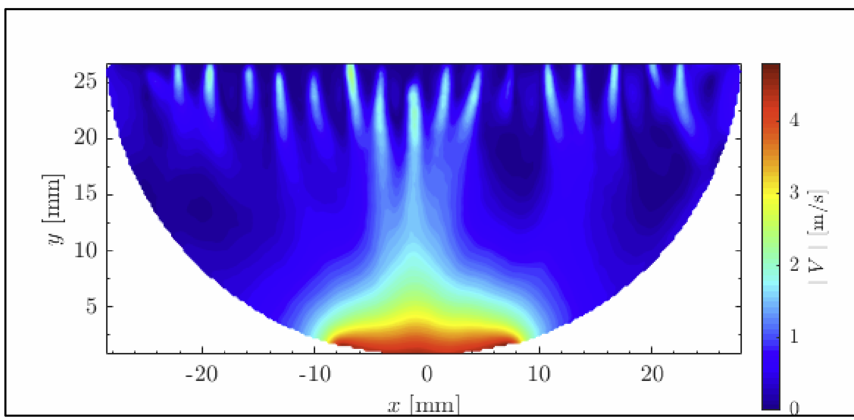


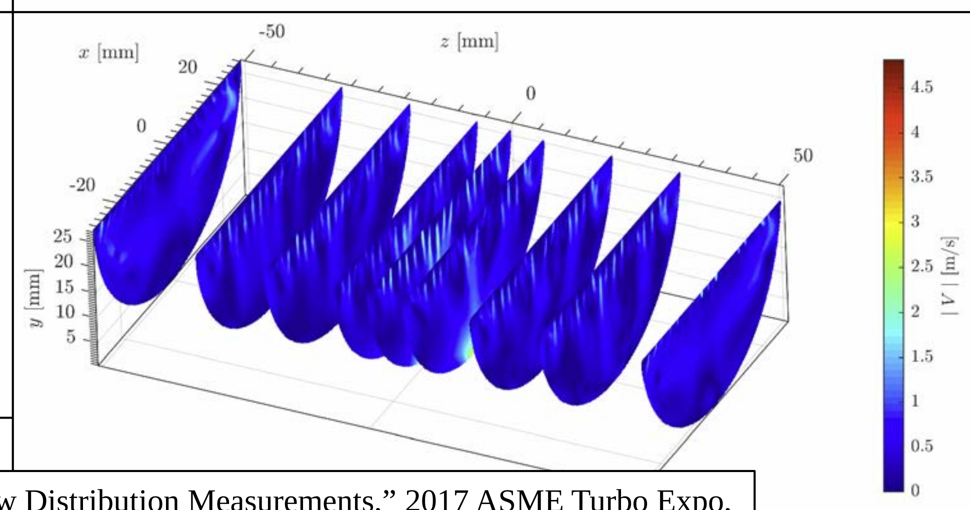
Alternative Headers:

Velocity magnitude was mapped out in space and reveals variations









Lance, B. W., Carlson, M. D., “Printed Circuit Heat Exchanger Flow Distribution Measurements,” 2017 ASME Turbo Expo, June 26-30, 2017, Charlotte, NC.

Lifetime Validation Testing

- Testing
  - Headers
  - Cores
  - Full Parts
- Flexibility
  - 1 to 10 ksi
  - 10 to 60 ksi
  - Remote operation
- Modes
  - Proof test
  - Burst test
  - Pressure fatigue
  - Thermal fatigue

CONCLUSIONS

Key Research Areas

- Lifetime validation of compact heat exchangers
  - Failure modes
  - Pressure/thermal/corrosion-assisted fatigue
  - Creep behavior and lifetime
  - Inspection and monitoring
- Affordable compact heat exchanger configurations
  - Configurations with large (gas/liquid) and small (sCO2) flow areas
  - Fabrication using advanced corrosion-resistant materials (nickels)
  - Tritium management for nuclear applications
- Methods to leverage low-cost materials at high temperature
  - Corrosion-resistant coatings for stainless steels
  - Coating failure potential and lifetime
  - Modular designs to allow for shorter lifetimes