SAND2019-1678PE

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

PCHE Thermal Fatigue Lifetime Validation and Trade-off Analysis for Various IHX Alloys

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TAL: Gary E. Rochau, Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY   NNSA National Nuclear Security Administration

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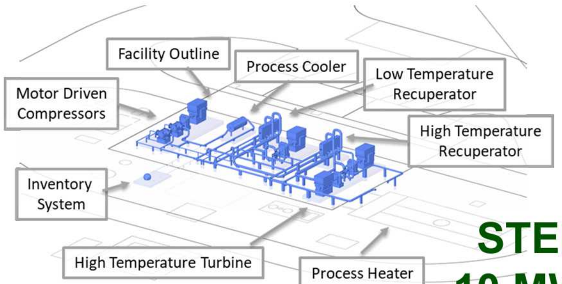
WHO: Advanced Heat Exchanger R&D Customer Base

VACUUM PROCESS ENGINEERING

COMPREX



STEP
10 MWe

Echogen
EPS100

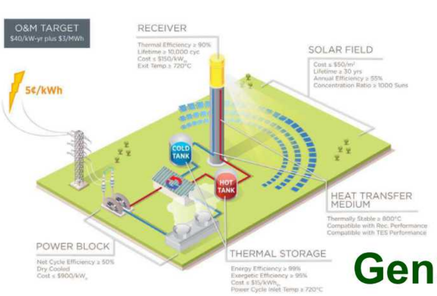
Original Equipment Manufacturers

System-Level R&D Projects

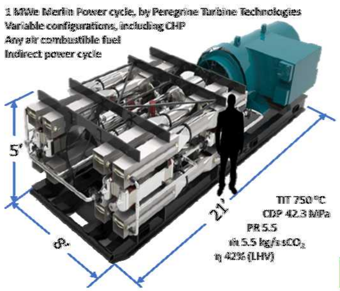
Commercial System Integrators

ALFA LAVAL

HEXCES



Gen3CSP
1 MWe



Merlin
1 MWe

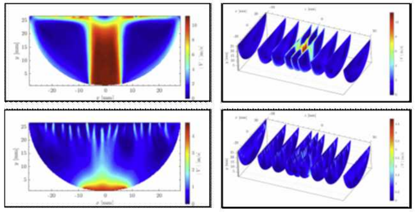
WHAT: Heat Exchanger R&D Needs – By Application

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			4-5	6-8	6-8	2	2-4	*500 to 1000*
CSP Tower with Thermal Storage	EE						8	2		2		4		4			4-5	6-8	6-8	2	2-4	*500 to 1000*
CSP Trough with Thermal Storage	EE						8			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		4-5															6-8	6-8	2	2-4	*230 to 650*
Gas Turbine Bottoming	FE		4-5															6-8	6-8	2	2-4	*230 to 650*
Municipal waste to energy	FE		4-5															6-8	6-8	2	2-4	*230 to 650*
10 MWe Pilot	FE		4-5														4-5	6-8	6-8	2	2-4	*550 to 700*
50 MWe Demonstration	FE		4-5														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							

PCHE Thermal Fatigue Lifetime Validation and Trade-off Analysis for Various IHX Alloys

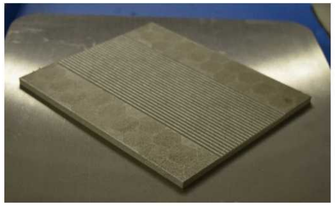
OEMs

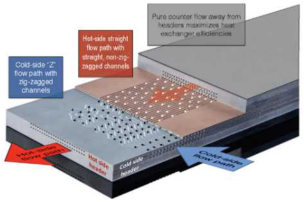
- Design Tools with Cost Optimization
- Joining of Nickel Alloys
- Thermal-hydraulic Validation
- Materials Compatibility Guidance
- Mechanical Lifetime Validation
- Design for Manufacturability/Scale-up



R&D

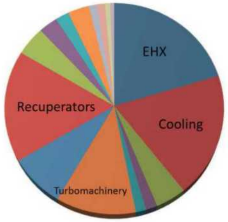
- Reduced Capital Cost
- Reduced Lead-time
- Design, Rating, and Simulation Tools





Industry

- Reduced Capital Cost
- Reduced Operating Cost
- Known Lifetime

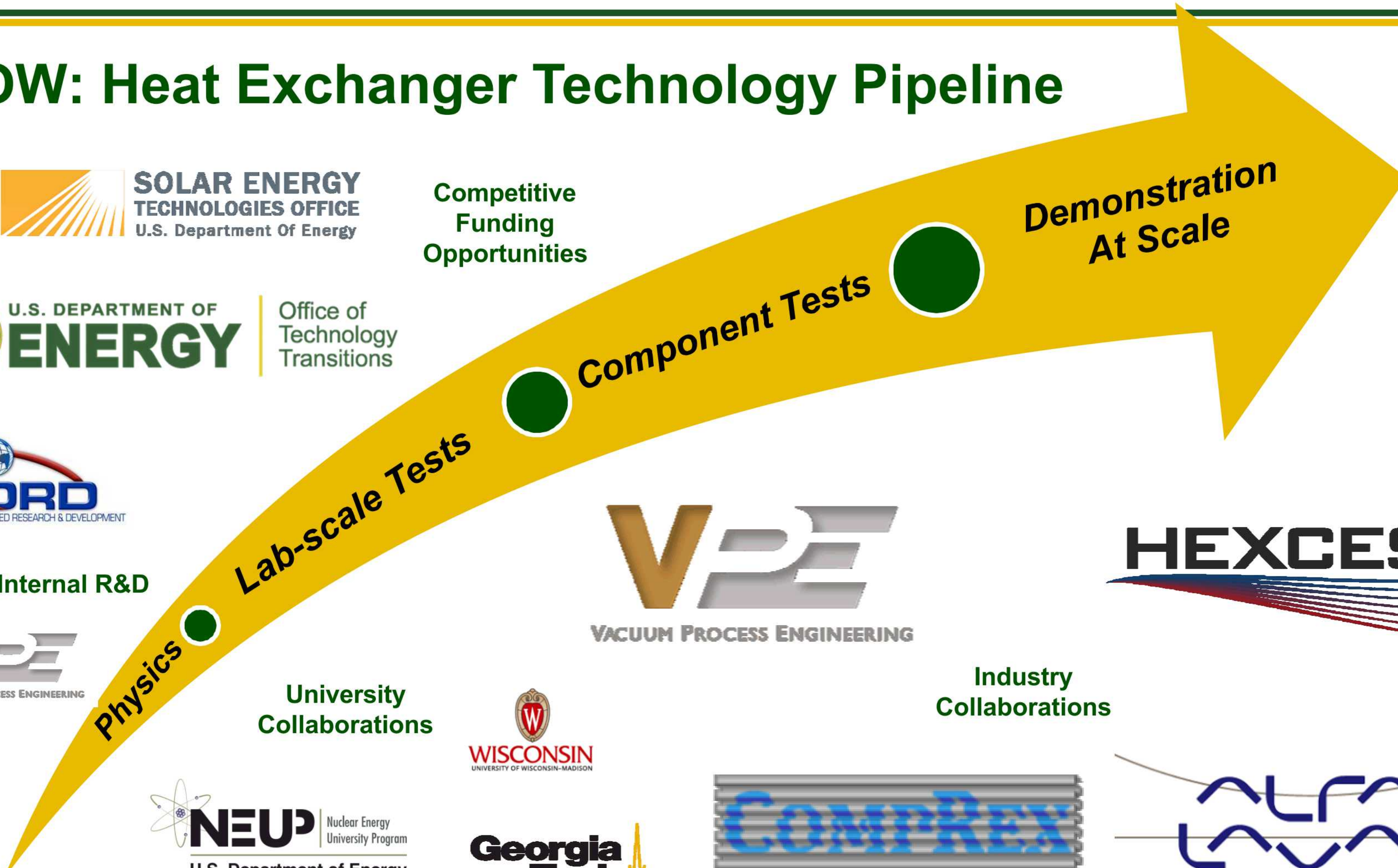


"[A] 30% reduction in HX cost would have [a] meaningful impact on system cost.[1]"

[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.

PCHE Thermal Fatigue Lifetime Validation and Trade-off Analysis for Various IHX Alloys

HOW: Heat Exchanger Technology Pipeline



SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Competitive Funding Opportunities

U.S. DEPARTMENT OF ENERGY | Office of Technology Transitions

LDRD
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Internal R&D

VPE
VACUUM PROCESS ENGINEERING

University Collaborations

WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON

NEUP Nuclear Energy University Program
U.S. Department of Energy

Georgia Tech

VPE
VACUUM PROCESS ENGINEERING

HEXCES

Industry Collaborations

COMPREX

ALFA LAVAL

Progress to Date, FY18 Plans, FY19+ Targets

Design Tools with Cost Optimization

Joining of Nickel Alloys

Thermal-hydraulic Validation

Materials Compatibility Guidance

Mechanical Lifetime Validation

Design for Manufacturability/Scale-up

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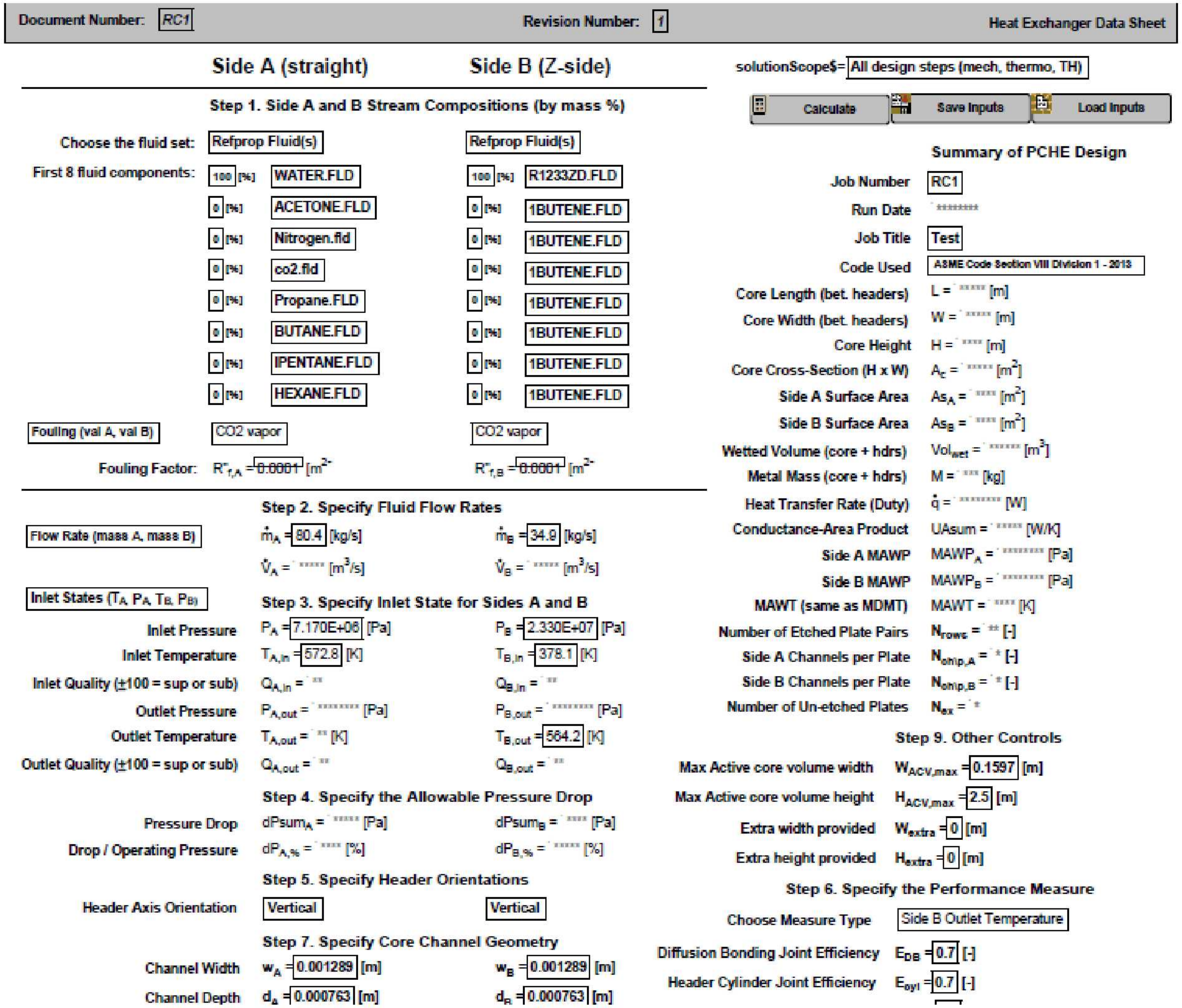
SEARCH Heat Exchanger Design Tool

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



PCHE Thermal Fatigue Lifetime Validation and Trade-off Analysis for Various IHX Alloys

OEMs — Design Tools with Cost Optimization

- Detailed design calculations including codes, standards, and cost
- Proprietary implementations to protect OEM trade secrets

R&D — Design, Rating, and Simulation Tools

- Flexible calculations to aid in optimizing system designs
- Relative cost to avoid price expectations with specific OEMS

Industry — Design and Rating Tools

- Flexible calculations to aid in optimizing system designs
- Inclusion in commercial system design codes (i.e. Aspen)

Next Steps for Design Tools with Cost Optimization

- ***Continue development of the VPE-proprietary SEARCH tool***
  - *CRADA funds-in*
  - *Contributes to reduced capital and operating costs*
- ***Provide a UUR SEARCH tool for other OEMs, R&D, and industry***
  - ***Funding source not yet identified***
  - *Interest so far from*
    - *OEMs - Heatric, HEXCES, Alfa Laval*
    - *R&D – SwRI, Georgia Tech*
  - *Contributes to reduced capital, operating costs, and lead-time*

Progress to Date, FY18 Plans, FY19+ Targets

Design Tools with Cost Optimization

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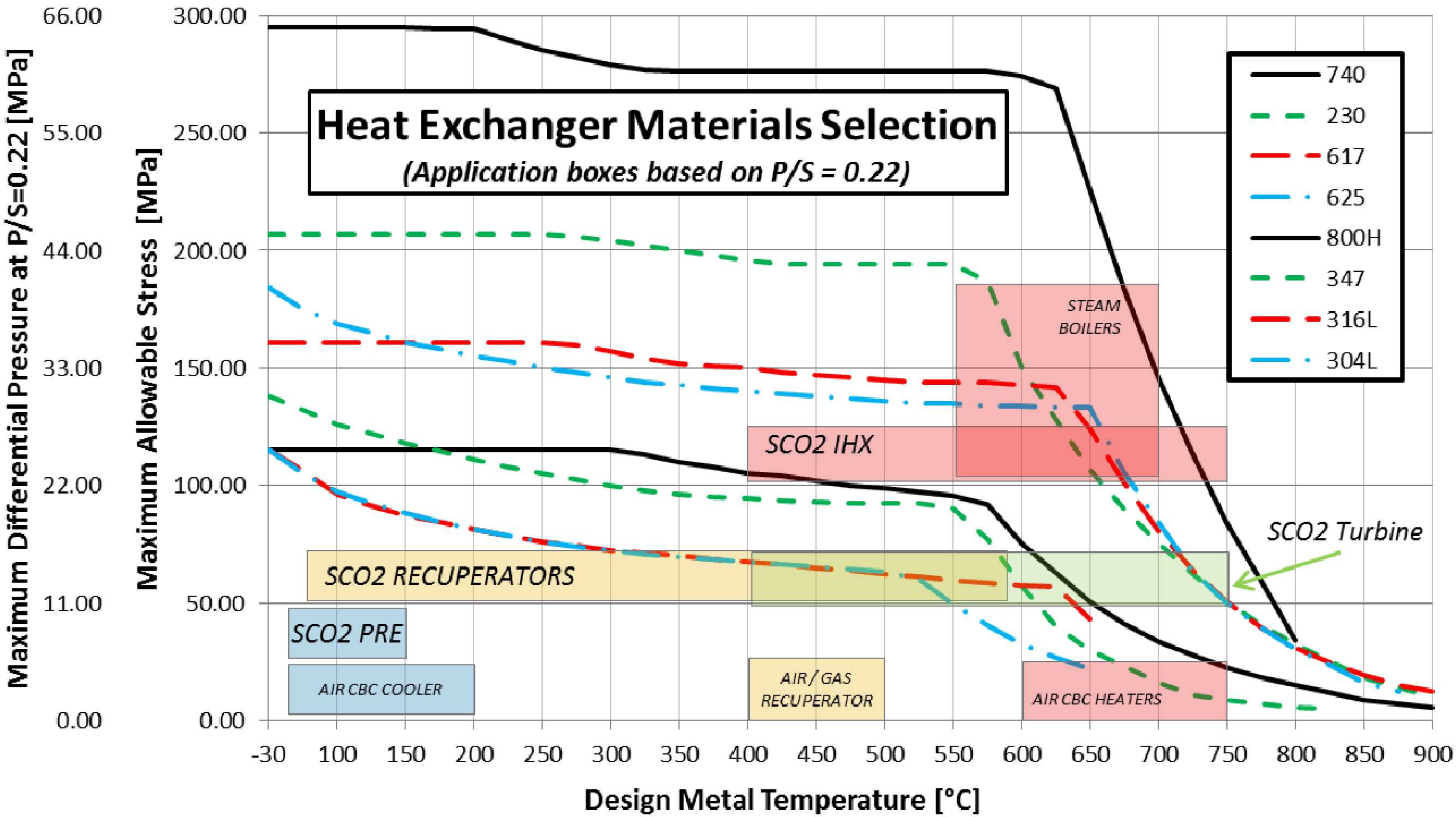
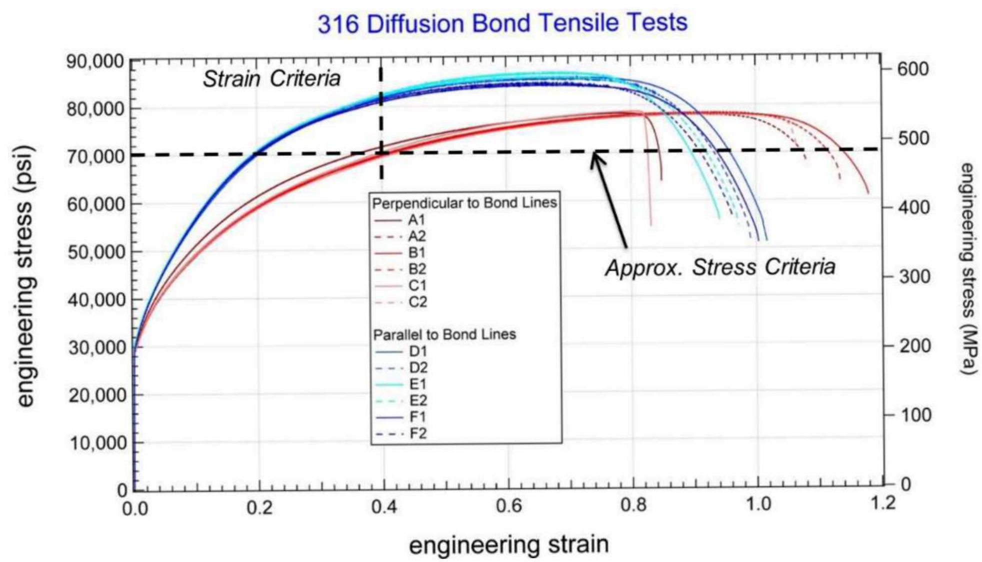
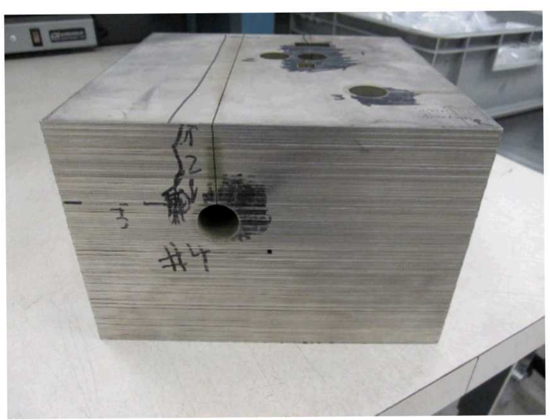


VPE Bonding Process Certification





Next Steps for Joining of Nickel Alloys

- ***Continue work toward nickel alloy diffusion bonds***
  - *IRP: ASME BPV code materials for nuclear service (800H, 316H SS)*
  - *SuNLaMP: Development of Inconel 625 bonds*
  - *SETO: Proposed development of Haynes 230 bonds*
  - *VPE CRADA: Exploring identified alternative materials (310CbN, 347H SS)*

Progress to Date, FY18 Plans, FY19+ Targets

Design Tools with Cost Optimization

Joining of Nickel Alloys

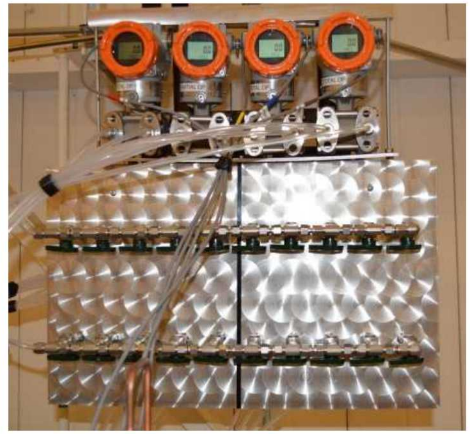
Thermal-hydraulic Validation

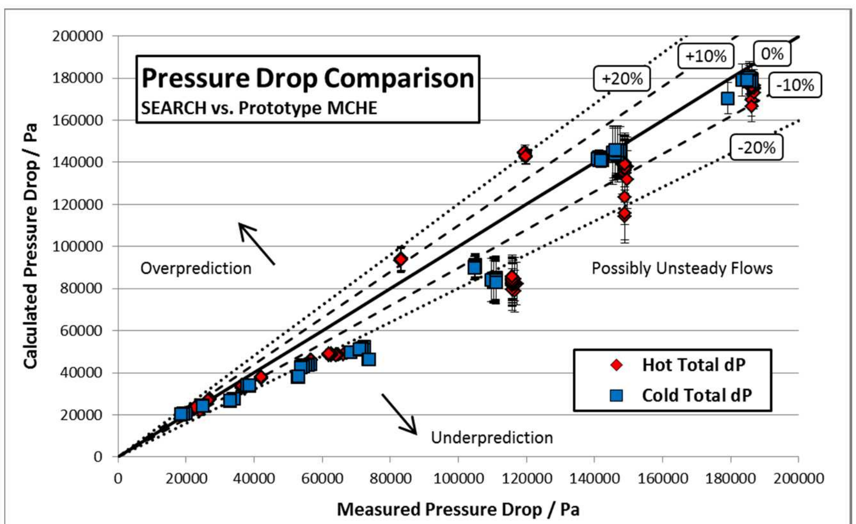
Materials Compatibility Guidance

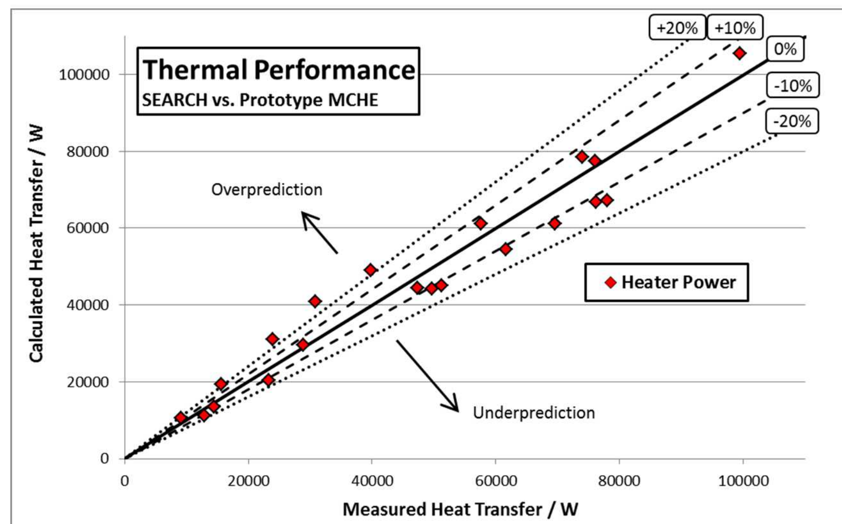
Mechanical Lifetime Validation

Design for Manufacturability/Scale-up

SEARCH Experimental Validation



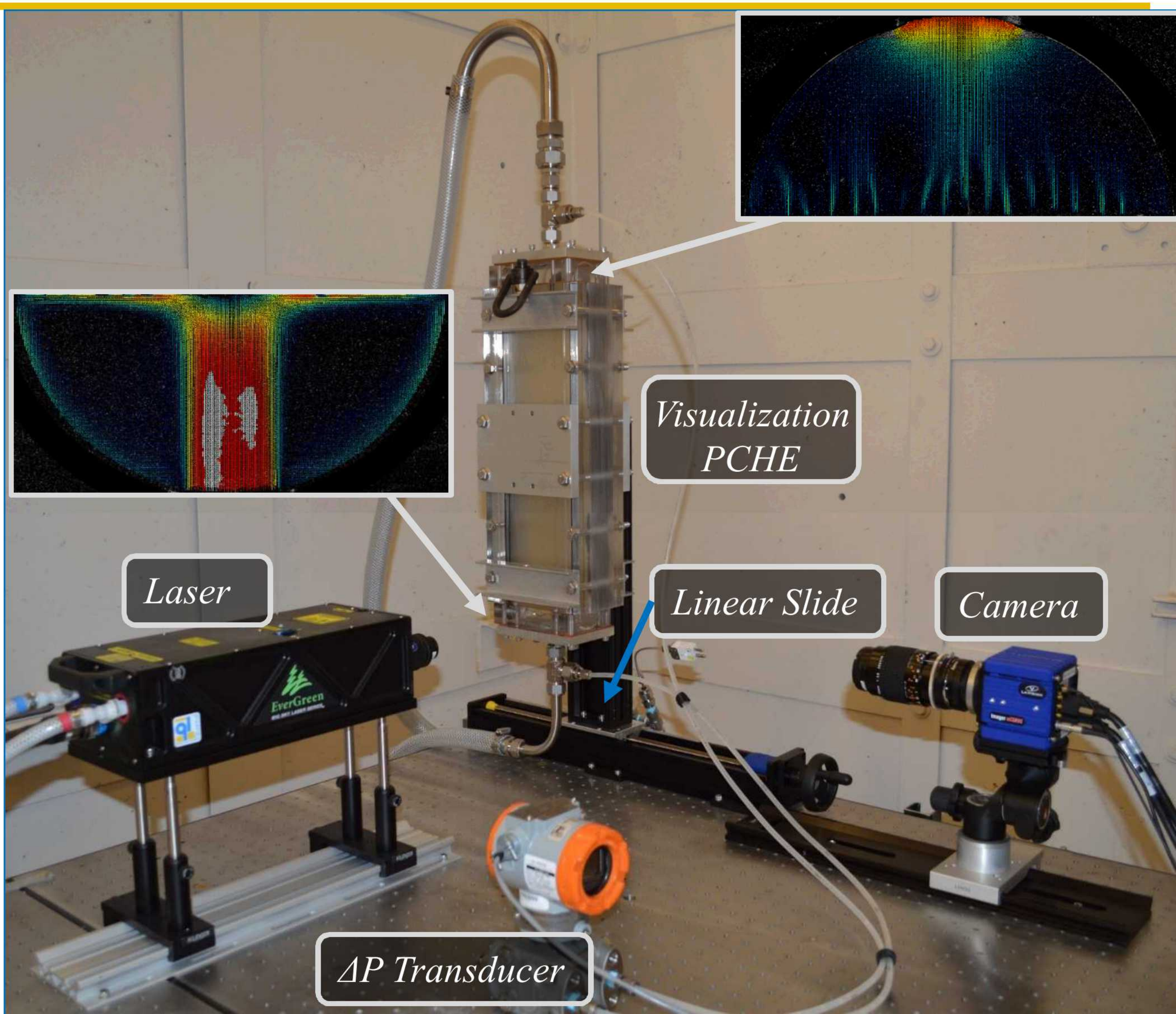




Alternative Headers:

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



Complementary Experiments and Simulations to Guide Flow Uniformity

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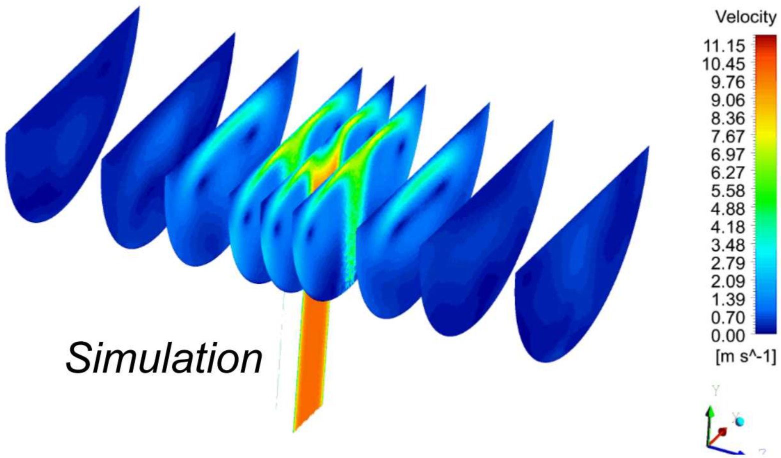
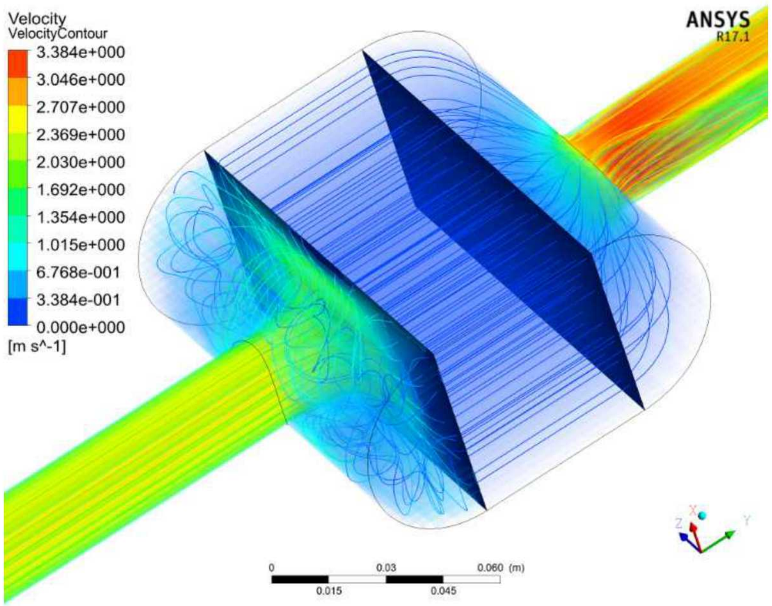
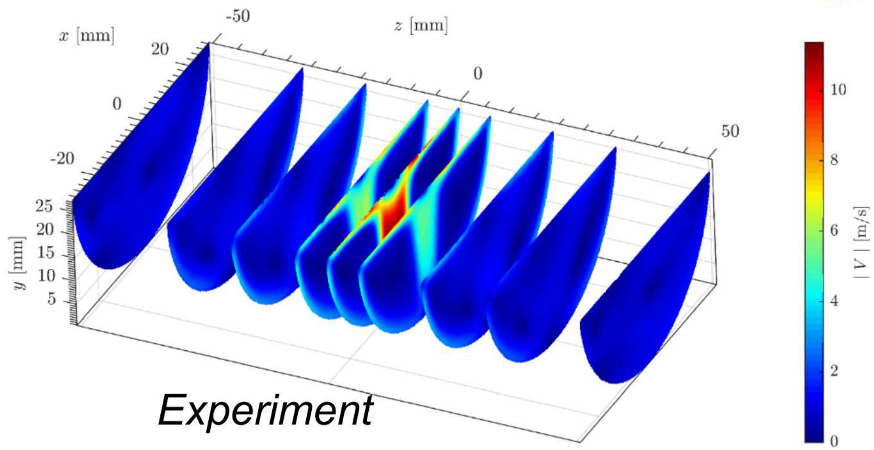
- Computational Fluid Dynamics (CFD) results comparison with experimental results in water
- Ideally extending to sCO_2 flow predictions



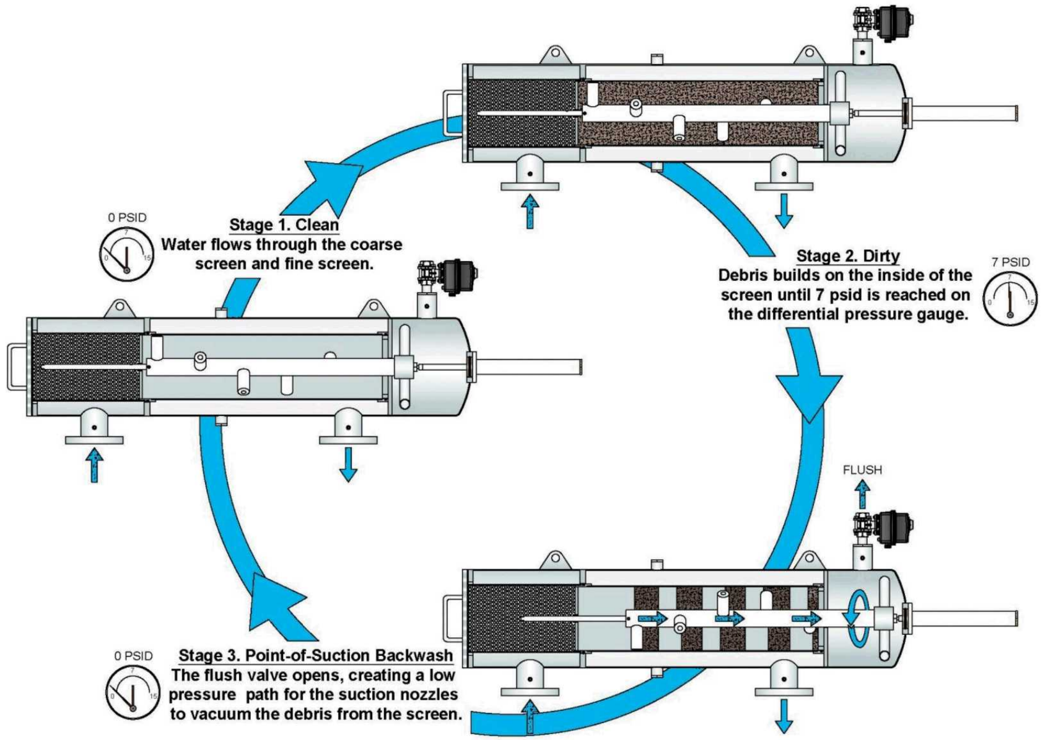




Lance, B. W., Carlson, M. D., "Microchannel Heat Exchanger Flow Validation Study," 2018 ASME Turbo Expo, June 11-15, 2018, Oslo, Norway.

Advanced Clean-in-Place Headers

- DOE OTT Technology Commercialization Fund (TCF) project with VPE
- Transferring Sandia-developed header designs to industry
- It is possible to design a header that can be cleaned in place, saving O&M costs
- Back-flushing is possible with a simpler method



https://www.forstafilters.com/wp-content/uploads/2014/06/180-Cycle.jpg

Next Steps for Thermal-hydraulic Validation

- ***Complete testing of Sandia-developed self-cleaning headers***
  - *FY18-19 funding only under a Technology Commercialization Fund award*
  - *Contributes to reduced operating cost and known lifetime needs*

- ***Support testing by other heat exchanger OEMs***
  - ***Not yet funded; interest by Comprex, Mezzo, and HEXCES***
  - *Contributes to reduced capital cost*

Progress to Date, FY18 Plans, FY19+ Targets

Design Tools with Cost Optimization

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PCHE Thermal Fatigue Lifetime Validation and Trade-off Analysis for Various IHX Alloys

Diffusion Bonding

- ASME BPV code-certified for stainless steels (304L, 316L, Duplex 2205) and titanium
- Development needed for 310, 347 SS, and nickels

Allowable Strength

- 316L SS has higher strength at temperature than other stainless steels and nickel alloys
- New ASME BPV material code cases take 10+ years

Corrosion

- Corrosion allowance values approach the wall thickness of compact heat exchangers
- More corrosion data is needed for different materials, temperatures, and environments

Next Steps for Materials Compatibility Guidance

- ***Complete materials trade-off analysis***
  - *FY19 funding under this work package (ART)*
  - *Contributes to reduced cost and known lifetime needs*
- ***Continued support of low-effort R&D and industry requests***
  - *No direct funding for this effort*
  - *Contributes to reduced cost and known lifetime needs*
- ***Continued coordination with the EC Materials Consortium***
  - *No direct funding for this effort*
  - *Contributes to reduced cost and known lifetime needs*

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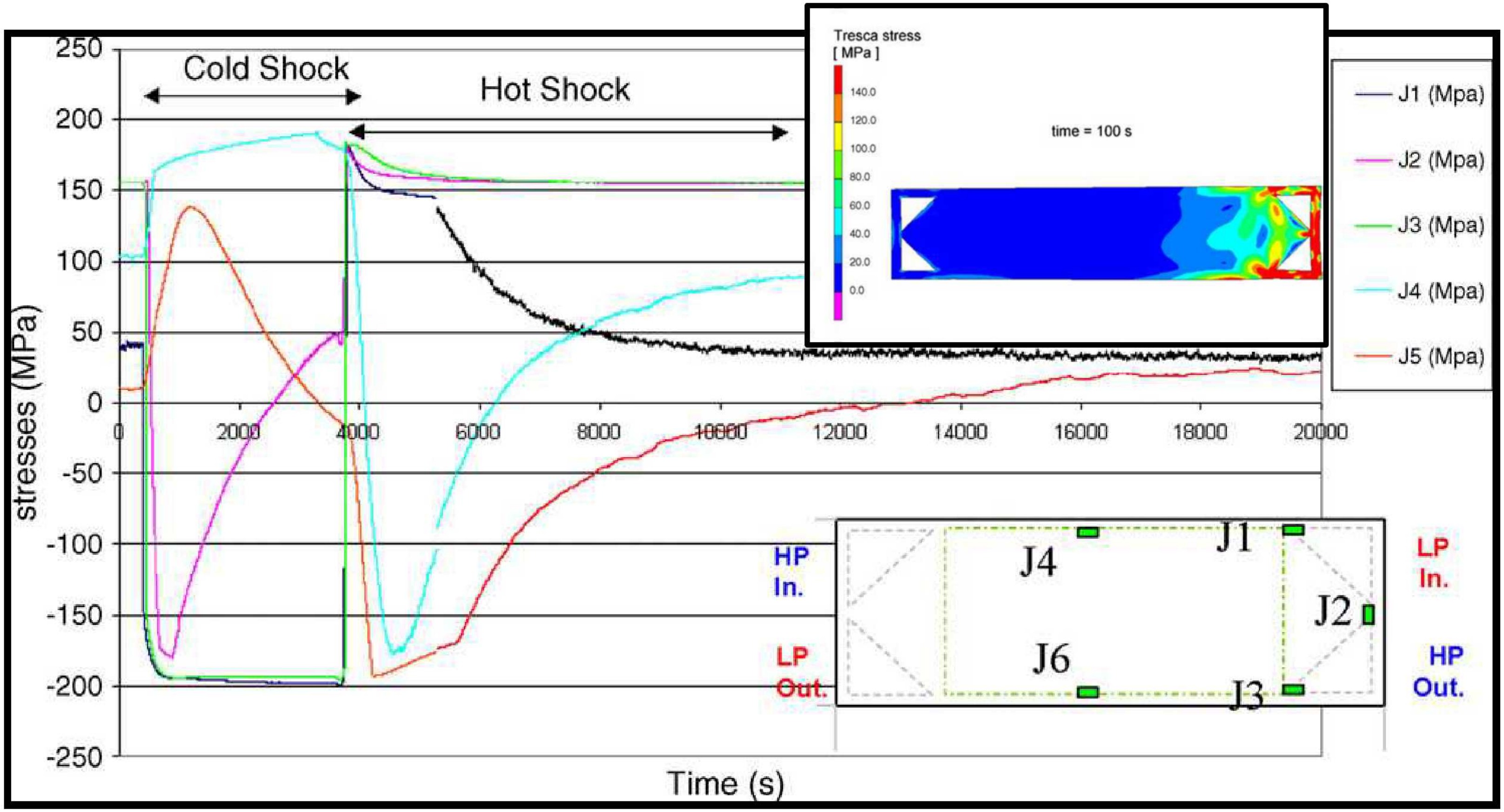
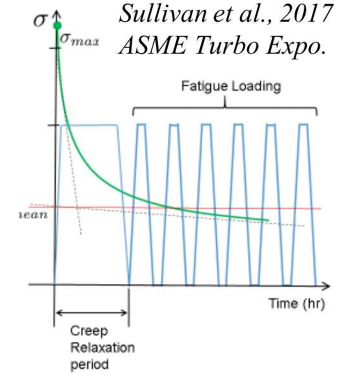
Lifetime Prediction



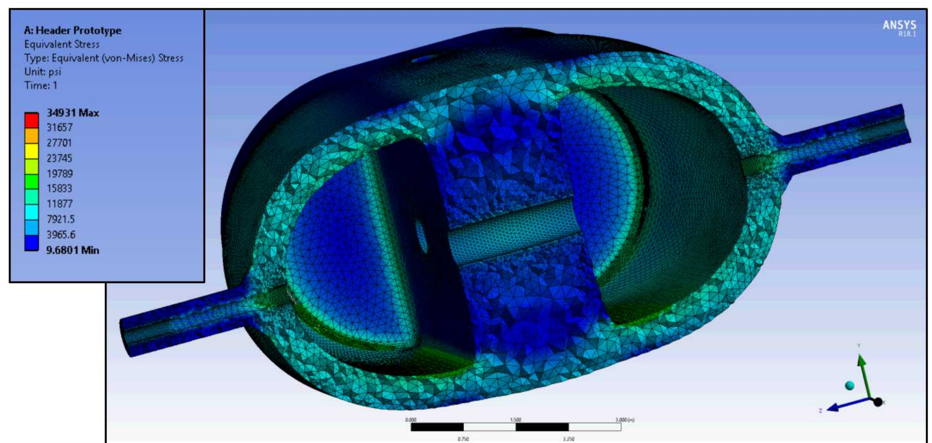
F. Pra, P. Tochon, C. Mauget, J. Fokkens, and S. Willemsen, "Promising designs of compact heat exchangers for modular HTRs using the Brayton cycle," Nuclear Engineering and Design, vol. 238, no. 11, pp. 3160–3173, Nov. 2008.

Pressure Fatigue and Burst Testing

- PCHE mechanical lifetime validation will reduce a potentially significant risk



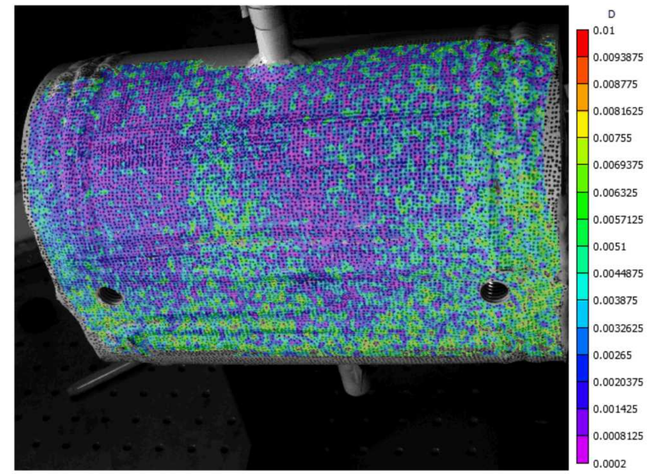
Sullivan et al., 2017 ASME Turbo Expo.

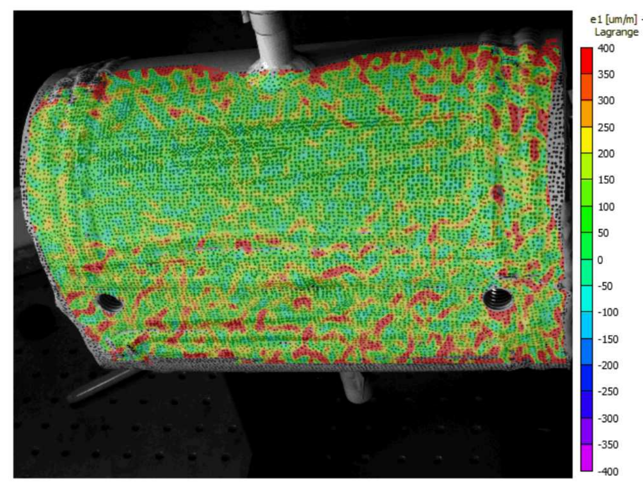


HPC4 MATERIALS for Severe Environments

PCHE Thermal Fatigue Lifetime Validation and Trade-off Analysis for Various IHX Alloys

D (mm)





$\mu\varepsilon_1$

Next Steps for Mechanical Lifetime Validation

- ***Begin PCHE header pressure-fatigue testing***
  - *FY18 funding under this work package (ART)*
  - *Contributes to reduced cost and known lifetime needs*
- ***Begin VPE hydrogen pre-cooler pressure-fatigue testing***
  - *FY18 funding under this work package (ART)*
  - *Contributes to reduced cost and known lifetime needs*
- ***Upgrade to pressure/thermal fatigue test capability***
  - ***Funding source not yet identified***
  - *Contributes to reduced cost and known lifetime needs*

Progress to Date, FY18 Plans, FY19+ Targets

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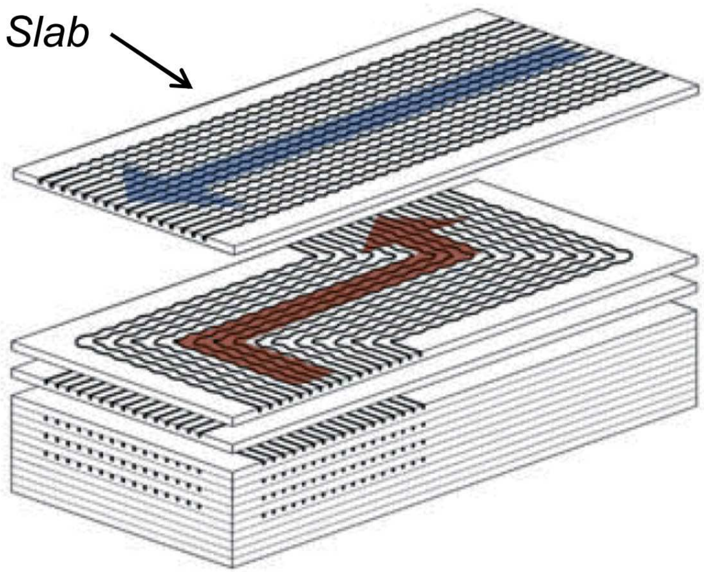
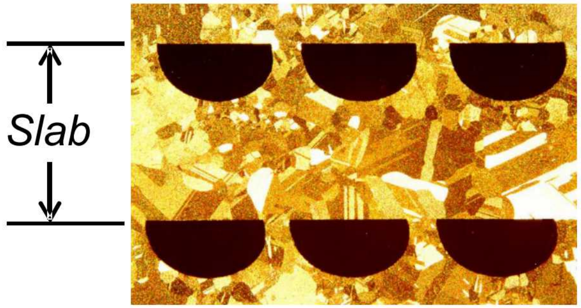
PCHE Thermal Fatigue Lifetime Validation and Trade-off Analysis for Various IHX Alloys

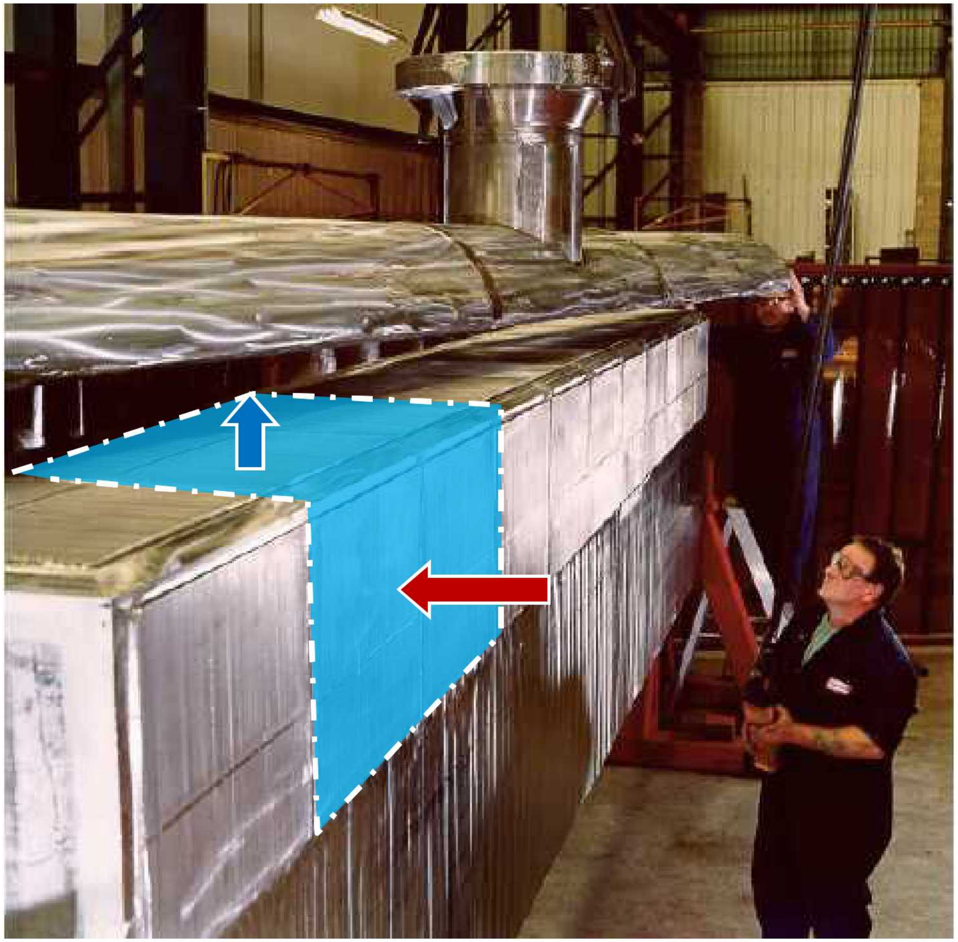
Heat Exchanger Core



Diffusion Bonding



Core and Manifold Assembly



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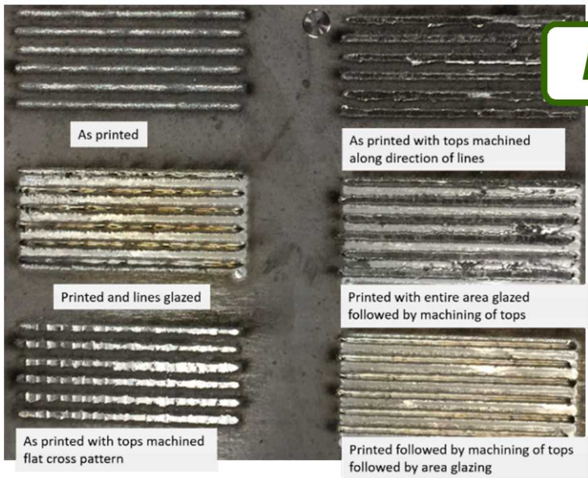
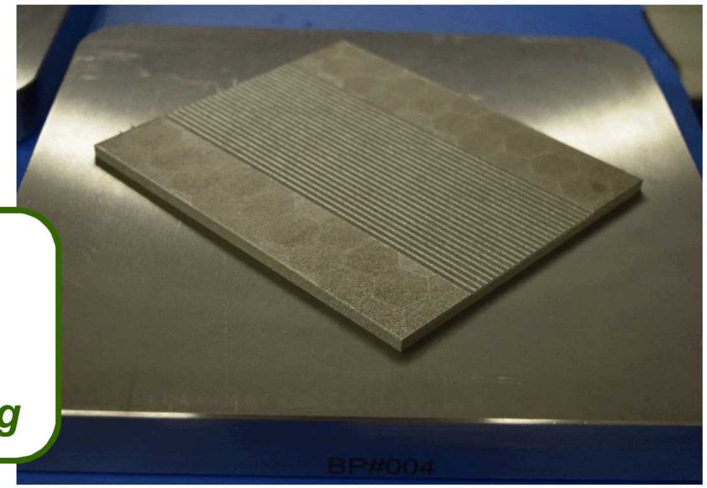
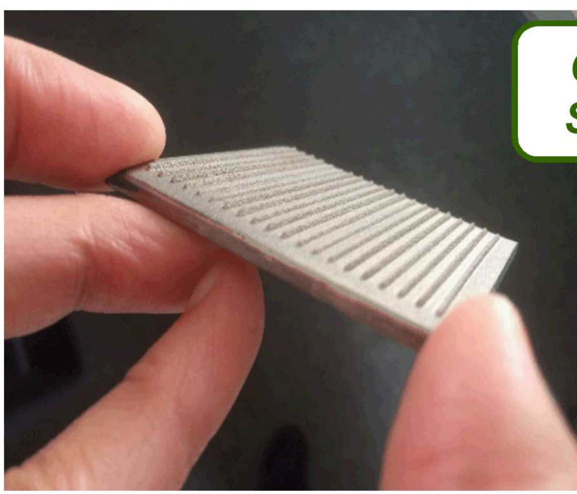


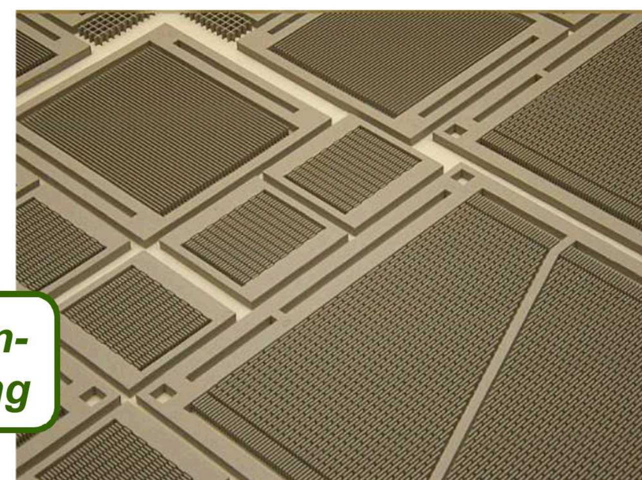
LENS



Direct Metal Laser Sintering



Cold-Spray



Screen-Printing

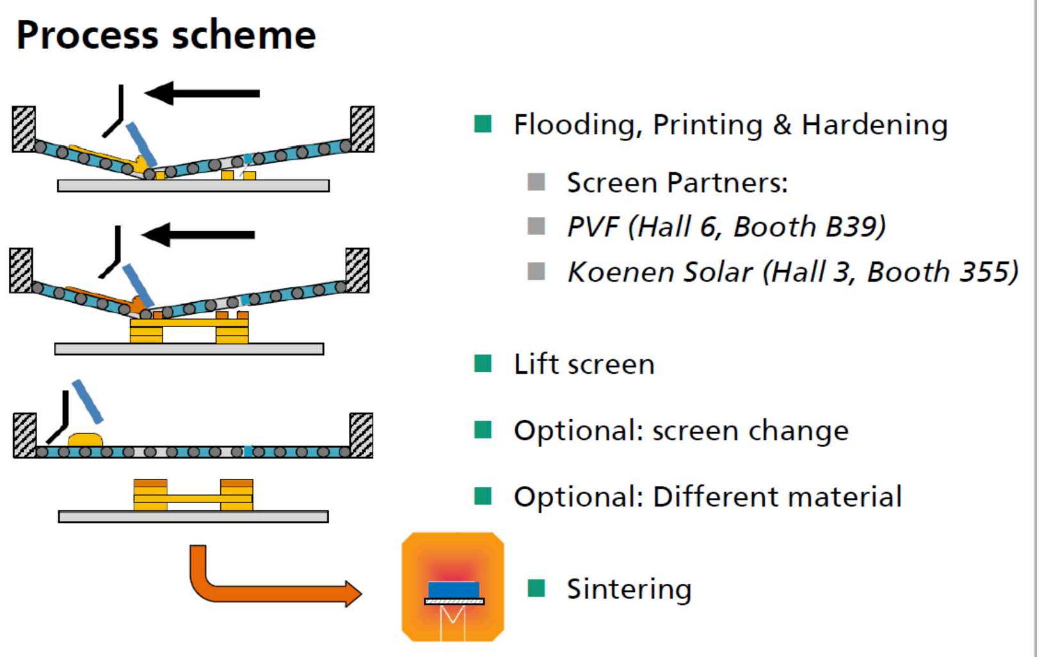
PCHE Thermal Fatigue Lifetime Validation and Trade-off Analysis for Various IHX Alloys

Sample	Yield [ksi]	UTS [ksi]	Elongation [%]
316L SS	25	70	40
LENS 1*	30.4	47.9	6.8
LENS 2*	27.3	48.8	9.7
Powder 1	28.6	62.0	27.6
Powder 2	28.3	66.1	25.5
Spray 1	31.9	73.4	29.5
Spray 2	30.9	71.9	27.4

**LENS Samples were 304L SS, others 316L SS*

3D Screen Printing for Heat Exchanger Shim Plates

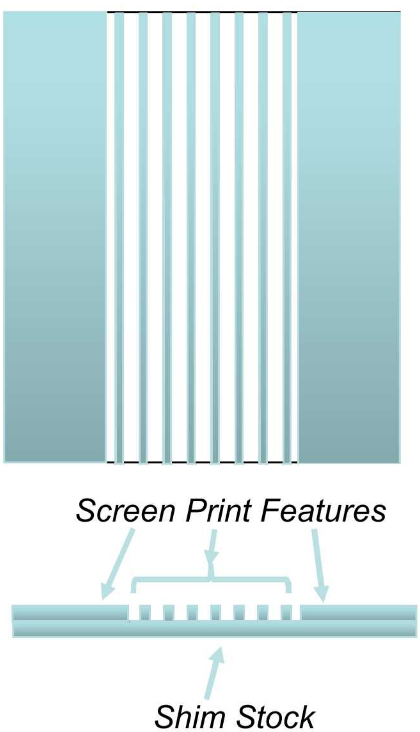
- *Work builds off recent developments at Fraunhofer IFAM*
- *SNL differentiated approach*
  - *Screen printing onto bulk substrates*
  - *Binder burnout process with pre-sintering to adhere particles together*
  - *Final sintering completed as part of diffusion bonding process*
  - *Control direction of shrinkage to avoid cracking of printed features*



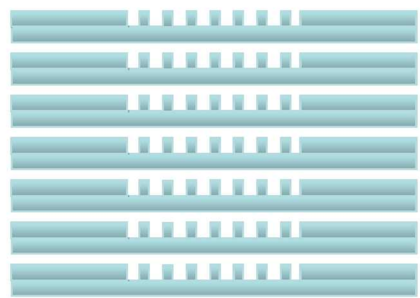
Curtesy Fraunhofer Institute IFAM Dresden

Screen Print, Burnout and Densification/Bonding

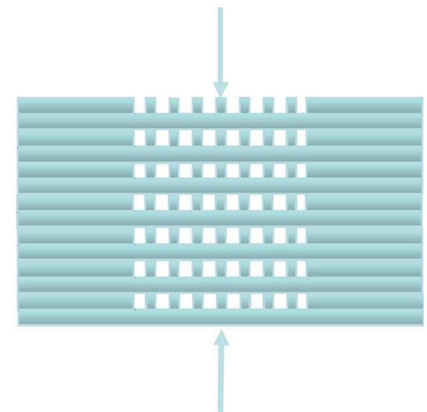
Screen Print Pattern on Metal Shim Stock



Stacked AM patterned shim plates



Pressure, Heat and Vacuum to Sinter Lines and Bond Plates



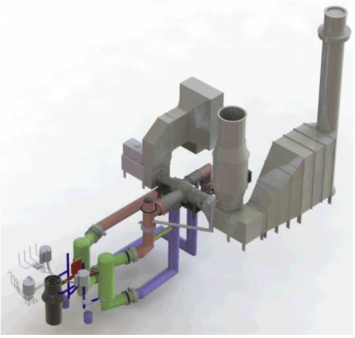
PCHE Thermal Fatigue Lifetime Validation and Trade-off Analysis for Various IHX Alloys

Next Steps for Design for Manufacturability/Scale-up

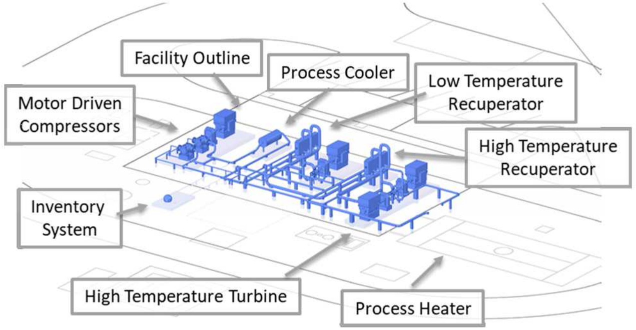
- ***Continue work on screen-printed hybrid additive shims***
  - *FY18 funding only under a Small Business Voucher project*
  - *Contributes to reduced cost and reduced lead-time needs*
- ***Exercise large bonding equipment to scale-up cores***
  - *Proposed collaborator under a Comprex Phase II SBIR proposal*
  - *Contributes to reduced cost and reduced lead-time needs*

Coordination, Collaboration, and Expertise

Nuclear Energy (FHRs)



Fossil Energy (STEP)



Solar Energy (G3P3)

Dry Cooling (PVNPP)

Conclusions

- Tracking who, what, and how for heat exchangers
- Research to address industry, R&D, and OEM needs
- Leveraging various funding sources
- Providing expertise to major DOE efforts