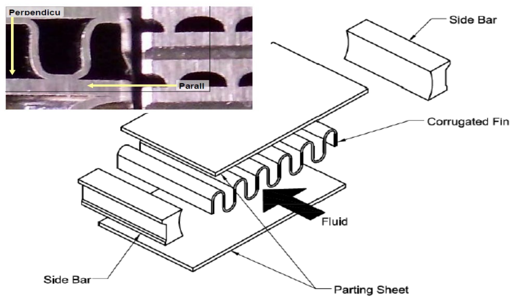
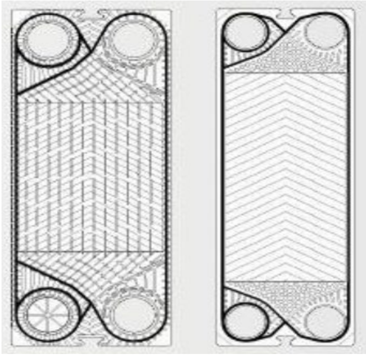
sCO_2 workshop 2019
UW-Madison perspective on heat exchangers

Mark Anderson

There are many different types of Types of advanced CHX and a lot of work looking at different materials for these HX

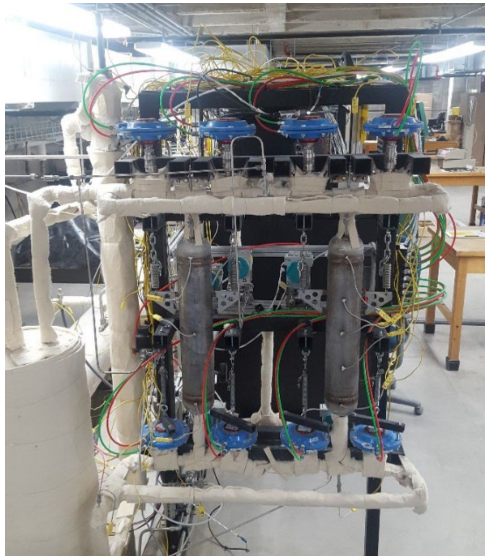


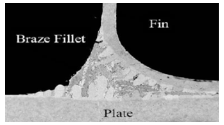
1.7 Brazed plate-fine heat exchanger

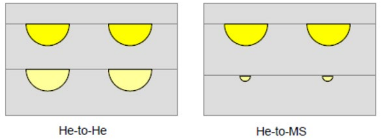


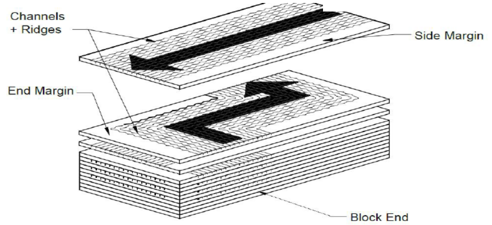
b) Fusion Bonded formed plate heat exchanger

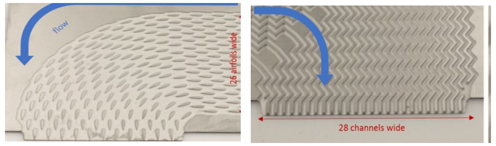
c) Brazed or Fusion bonded unit cell heat exchanger



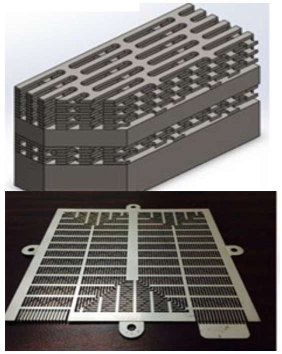






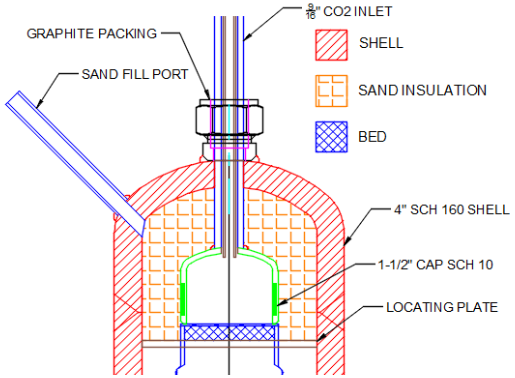


d) Surface etched and formed fusion bonded PCHE – Discrete –versus continuous channel



e) Through etched Fusion Bonded PCHE

f) Micro-tube CHX

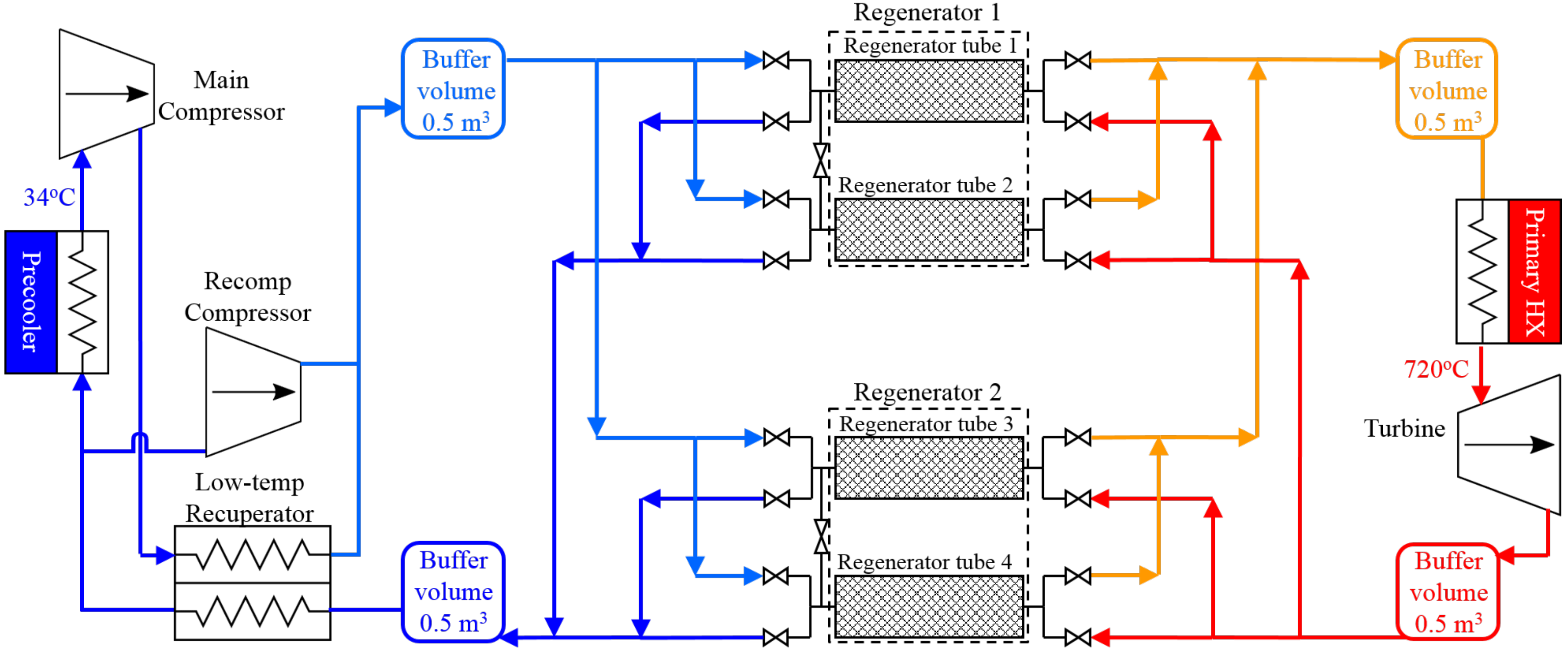


Switch bed regenerators canbe used in place of recuperators in sCO2 cycle with some advantages

Cycle simulation in gPROMS incorporates regenerators with other BOP components

- Components sized for 10 MWe nominal power output
- Bed linking valves reduce carryover through compressor
- Low-temp recuperator – “mixed” regenerative system
- Buffer volumes (modeled as well-mixed tanks) approximate pipe and header volume
- Fixed TM shaft speed (all on same shaft)
- Regenerator switching enforced by controlling valve stem positions

T_{amb} = 25°C
$\varepsilon_{LTR} = 0.92$
$\eta_{s,turb} = 0.88$
$\eta_{s,C} = 0.85$



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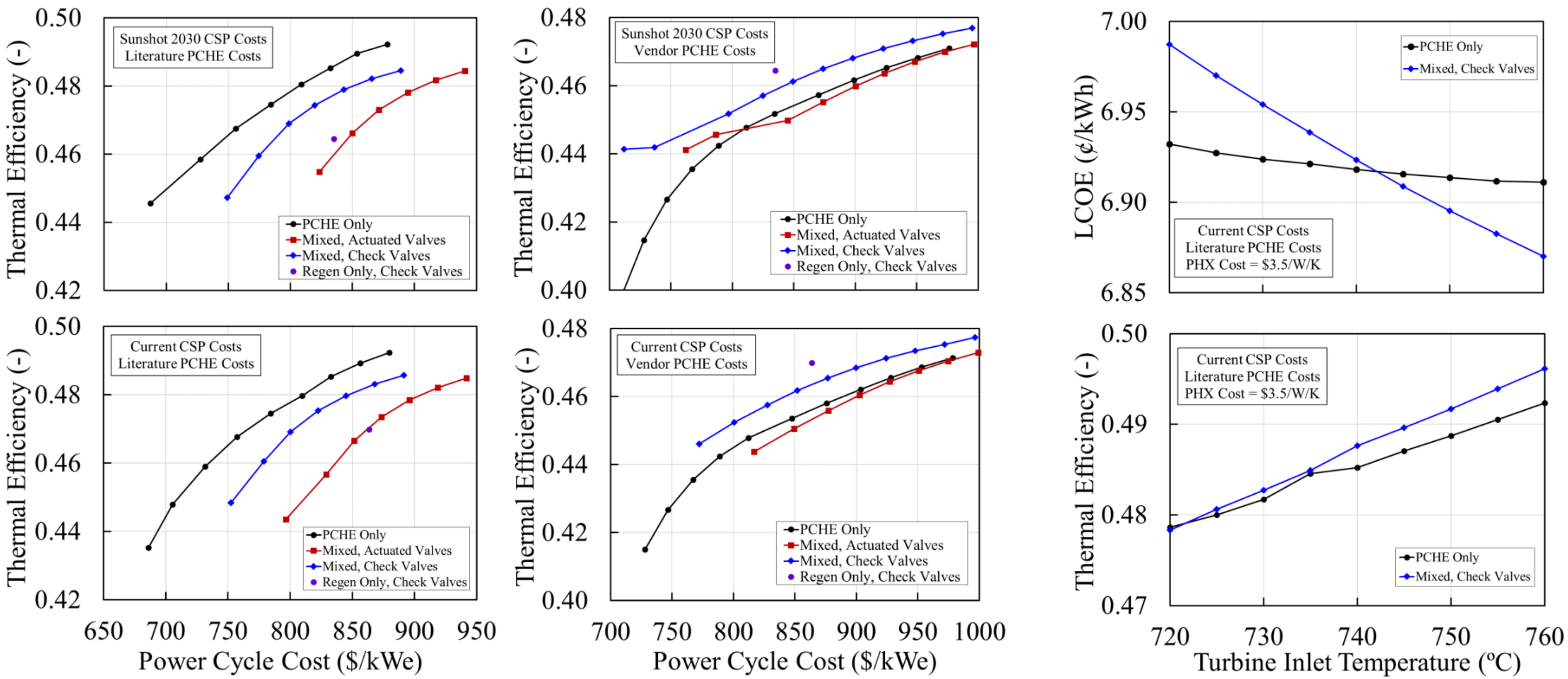
Evan Reznicek – CSM/NREL

The relative economic benefit of regenerators depends heavily on cost of recuperators



Increased temperatures

LCOE cost ~ equal to recuperators – slightly more expensive assuming 316 PCHE
Some additional possible benefits

- Can operate at higher temps
- Serviceable
- Cost starts to become lower at higher temperatures
- Some benefits if there are issues with PCHE’s (fouling/failure)

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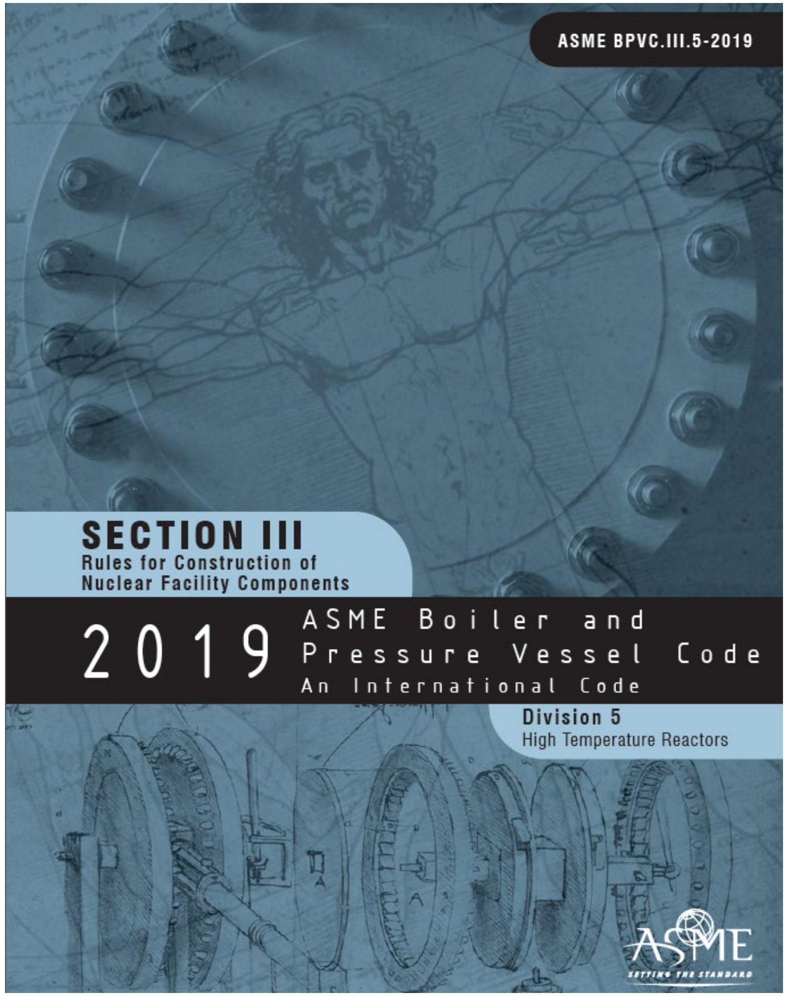
Evan Reznicek – CSM/NREL

- Use for power production requires ability to build and stamp Heat Exchangers to ASME Code. This means bond has to meet base metal. Need to build with materials in code.

- Need to have method for In-service inspection.

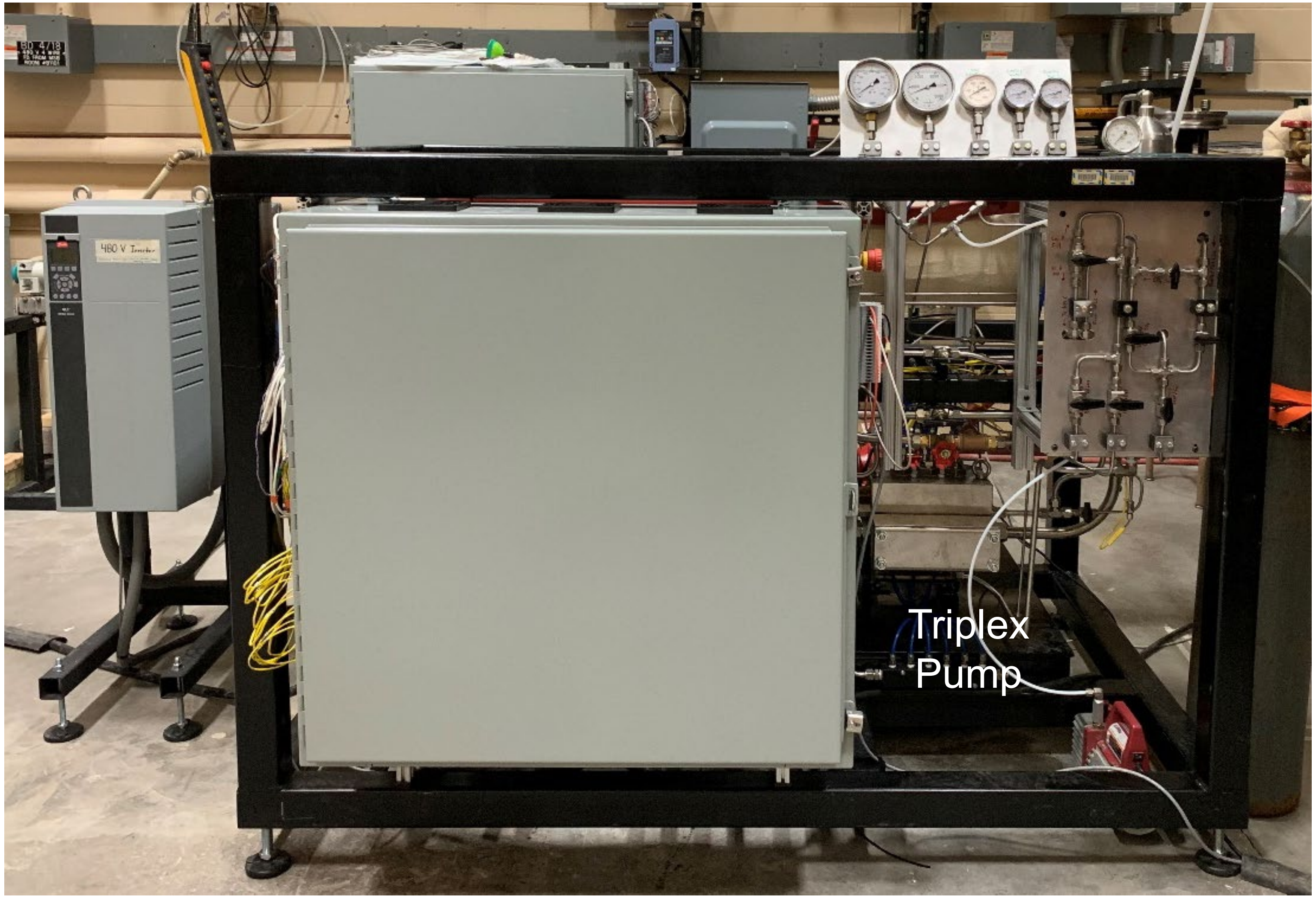
- Need to develop an understanding of operational issues of heat exchangers under these harsh operating conditions



Report to the DOE: 1630-0001-RPT-001, Revision 0, ASME Code Case for Compact Heat Exchanger Draft Code Case and Gap Analysis
Publication: ICONE27-1138 Potential ASME Code Case for Construction of Compact Heat Exchangers in High Temperature Reactors

Testing of PCHE between salt and sCO_2

Test Unit #1



sCO2 pump cart 4300 psi, 0.8 kg/s, 650^{o}C

Test Unit #1

Nitrate Salt – CO_2
($0.6\ NaNO_3 + 0.4\ KNO_3$)

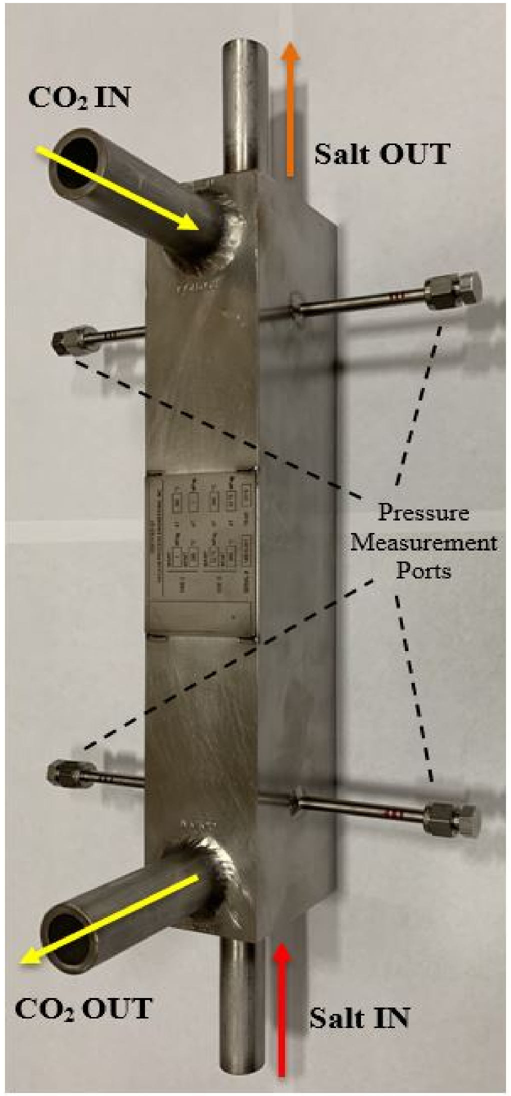
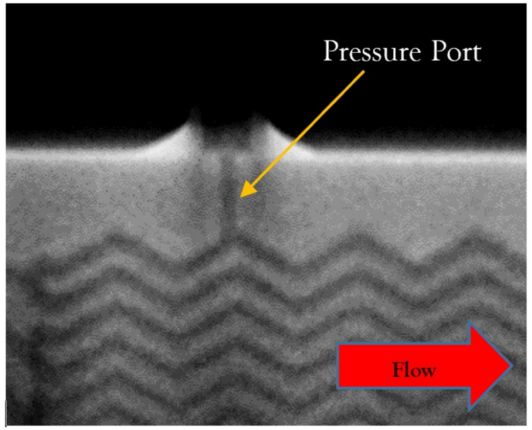


Table 2. Design Specification for *Test Unit #1 [UW]*

Design Parameter	HOT (Solar Salt)	COLD (CO_2)
Design Pressure	1.00 MPa (145 psi)	22.75 MPa (3300psi)
Design Temperature	560° C	
Overall HT coefficient	2275.1 W/m^{2}K	
Heat Duty	27 kW	
Mass Flow Rate	0.35 kg/s	0.16 kg/s
Inlet/Outlet Temperature	550/500° C	400/540° C
Estimated Pressure Drop	0.1 MPa (14.5 psi)	0.15 MPa (21.8 psi)
Core Dimensions	2.26” x 13.56” x 2.88” (*0.00144 m^3*)	



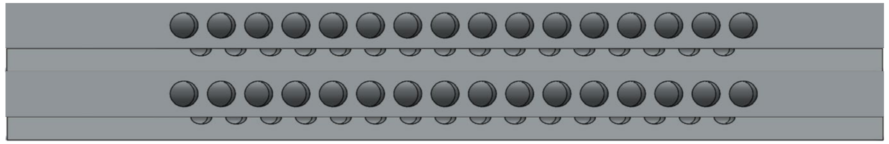
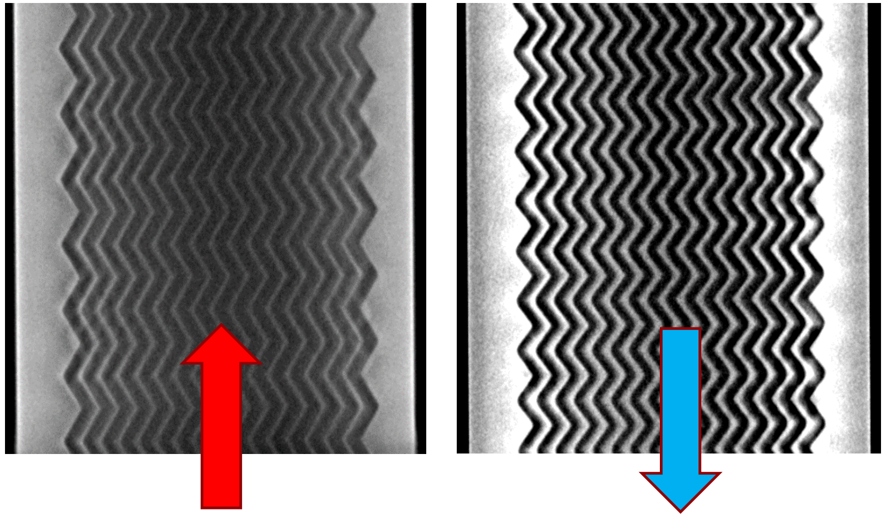
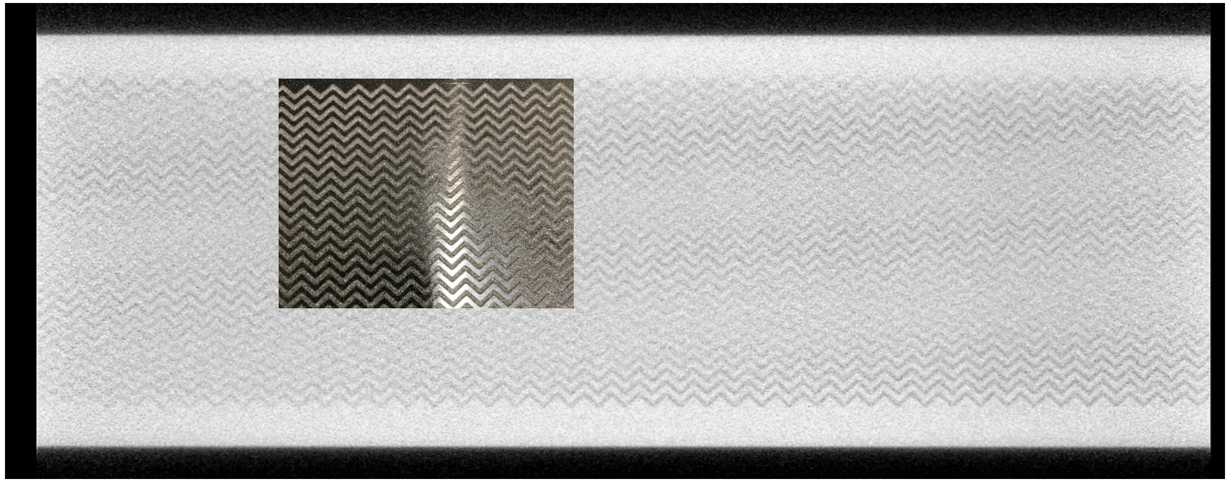


Table 3. Internal Geometry Details for Test Unit #1

Geometric Characteristic	HOT (Solar Salt)	COLD (CO_2)
Compactness Factor	415 m^{-1}	



800H CO_2 Recuperator



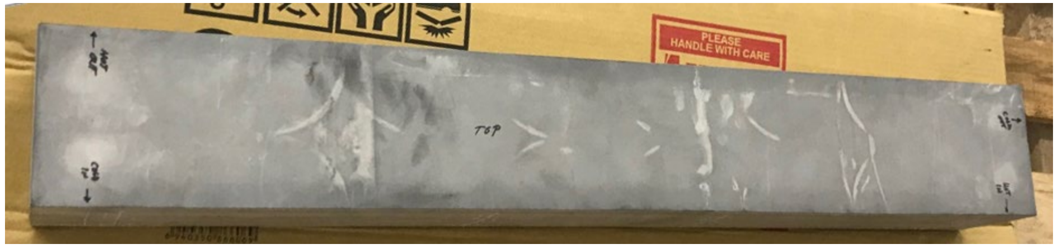


Table 1. Design Specification for 800H Recuperator

Design Parameter	HOT (CO_2)	COLD (CO_2)
Design Pressure	27.5 MPa (4000 psi)	27.5 MPa (4000 psi)
Design Temperature	660° C	
Overall HT coefficient	2719 W/m^{2}K	
Heat Duty	237 kW	
Mass Flow Rate	0.3 kg/s	0.3 kg/s
Inlet/Outlet Temperature	650/85° C	50/592° C
Estimated Pressure Drop	0.32 MPa (46.5 psi)	0.31 MPa (46.0 psi)
Core Dimensions	4.26” x 3.83” x 30.1”	

Test Units #2 and #3

800H Helium – CO_2

800H FLiNaK – CO_2

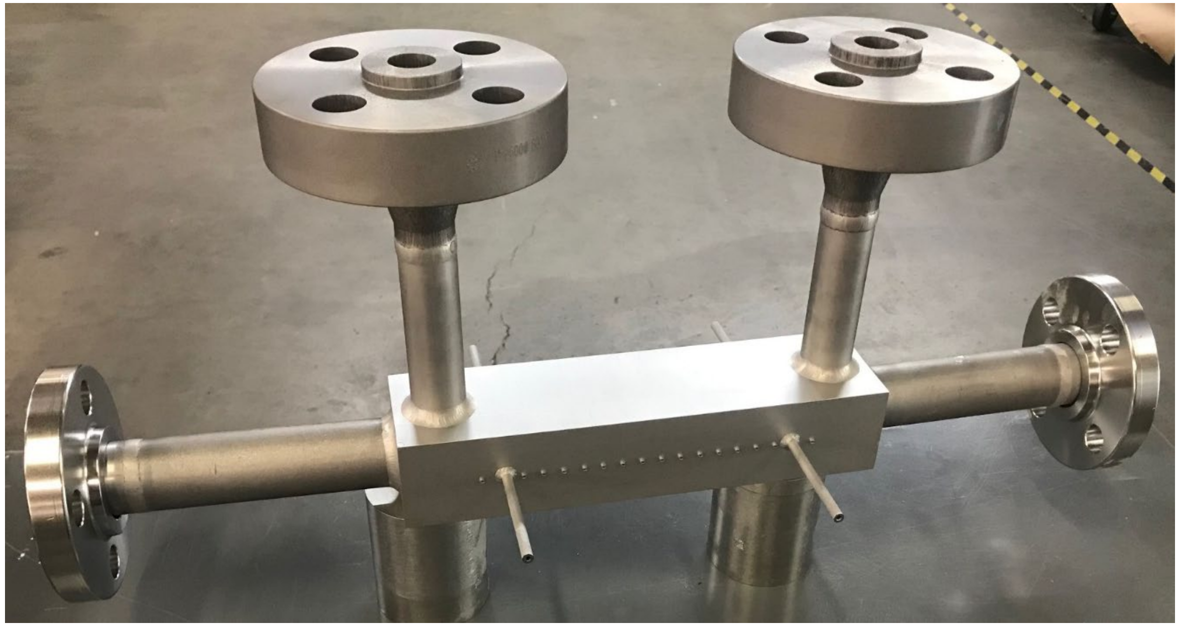


Table 4. Design Specification for *Test Unit #2 [GT]*

Design Parameter	HOT (Helium)	COLD (CO_2)
Design Pressure	3.30 MPa (480 psi)	22.0 MPa (3190 psi)
Design Temperature	570° C	
Overall HT coefficient	1705 W/m²K	
Heat Duty	6.5 kW	
Mass Flow Rate	0.007 kg/s	0.03 kg/s
Inlet/Outlet Temperatures	550/374° C	350/527° C
Estimated Pressure Drop	0.168 MPa (24.4 psi)	0.023 MPa (3.5psi)

Table 5. Design Specification for *Test Unit #3 [UM]*

Design Parameter	HOT (FLiNaK)	COLD (CO_2)
Design Pressure	0.5 MPa (73 psi)	16.5 MPa (2390 psi)
Design Temperature	720° C	
Overall HT coefficient	1729 W/m²K	
Heat Duty	15.4 kW	
Mass Flow Rate	0.20 kg/s	0.06 kg/s
Inlet/Outlet Temperatures	700/661° C	500/694° C
Estimated Pressure Drop	0.043 MPa (6.3 psi)	0.088 MPa (12.8 psi)

Test Unit #4

800H Sodium– CO_2

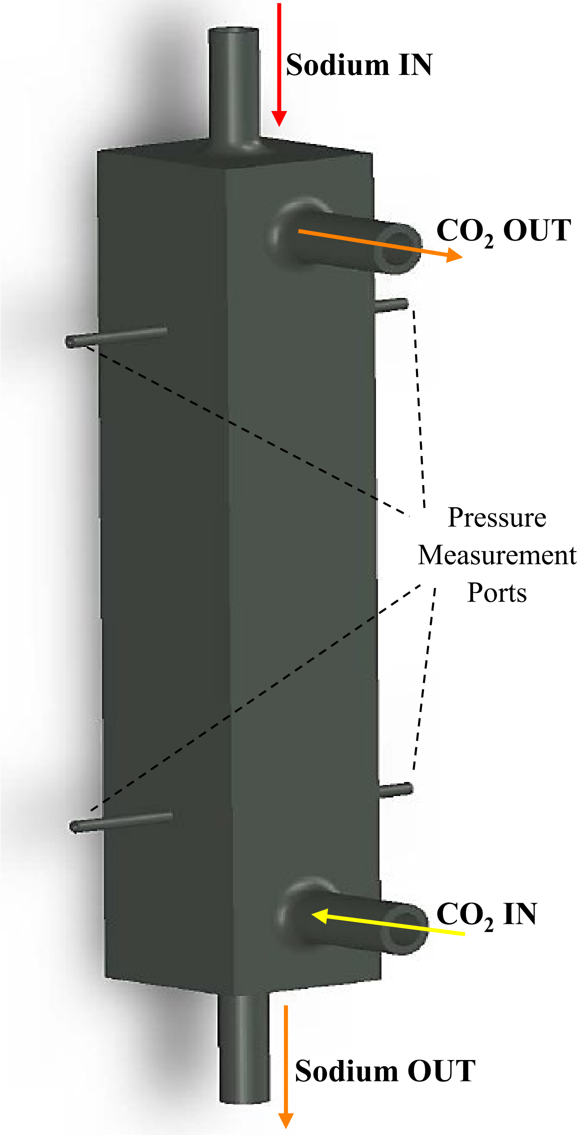


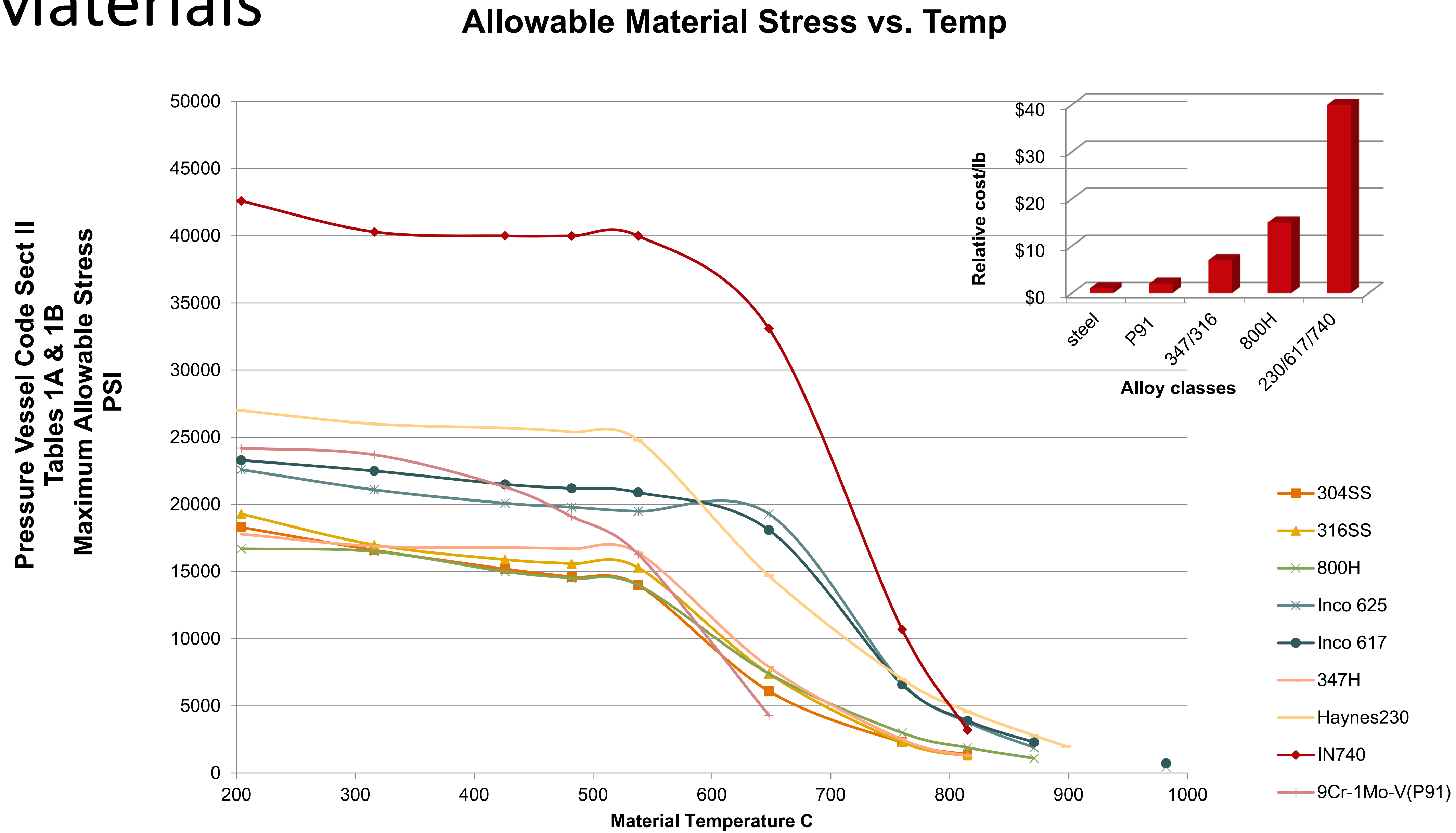
Table 6. Design Specification for *Test Unit #4 [UW]*

Design Parameter	HOT (Sodium)	COLD (CO_2)
Design Pressure	1.50 MPa (218 psi)	26.40 MPa (3830 psi)
Design Temperature	720° C	
Overall HT coefficient	3180 W/m²K	
Heat Duty	19 kW	
Mass Flow Rate	0.30 kg/s	0.25 kg/s
Inlet/Outlet Temperatures	600/550° C	540/595° C
Estimated Pressure Drop	0.011 MPa (1.5 psi)	0.195 MPa (28.3psi)

Characteristics:

- Straight circular sodium channels
- Compatible with fiber instrumentation

Materials



Allowable Material Stress vs. Temp
Pressure Vessel Code Sect II
Tables 1A & 1B
Maximum Allowable Stress
PSI
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
200
300
400
500
600
700
800
900
1000
Material Temperature C
Relative cost/lb
$40
$30
$20
$10
$0
steel
P91
347/316
800H
230/617/740
Alloy classes
304SS
316SS
800H
Inco 625
Inco 617
347H
Haynes230
IN740
9Cr-1Mo-V(P91)

Materials

316/316L - good bonding and there are significant units in service using this alloy. Lower cost and is acceptable for low temperature recuperator – probably at the limit for high temperature recuperator – from a corrosion aspect.

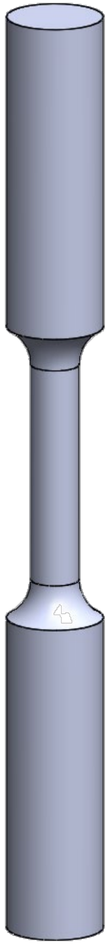
Higher temperature materials 740H, H282, H230, IN617, IN625, others are available for use but not much bonding experience or operational experience.

Nuclear qualified materials section III, also requires high temperature tensile, creep and creep fatigue data

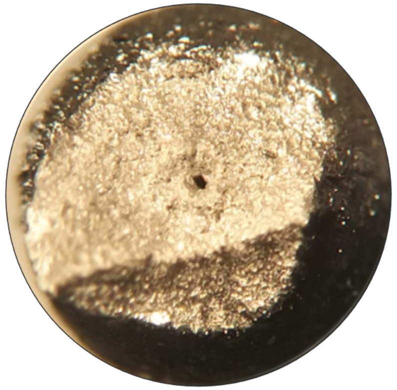
- Materials: 2-1/4Cr–1Mo ferritic steel, Type 304H stainless steel, Type 316H stainless steel, Alloy 800H, and modified 9Cr-Mo-V [Grade 91] ferritic steel. Soon Alloy 617 will be included as well, since it is a code case currently being balloted. Alloy 718 is available in Division 5 for high temperature bolting.
- 316H provides good bonding but is not available in the market in thin sheets (only thick plates are available) – modest strength at temp – modest corrosion resistance.
- Alloy 800H is solid solution strengthened, iron-nickel-chromium alloy. It has high creep and stress rupture properties. It is suited for long-term exposure to high temperatures where corrosion resistance is needed.
- IN617 – solid-solution, strengthened, nickel-chromium-cobalt, molybdenum alloy. good high temperature strength and corrosion resistance but limited current use and availability is scarce.

Rupture surfaces from tension tests at RT

Tasnim Hassan thassan@ncsu.edu
Heramb Mahajan hpmahaja@ncsu.edu



Tension specimen

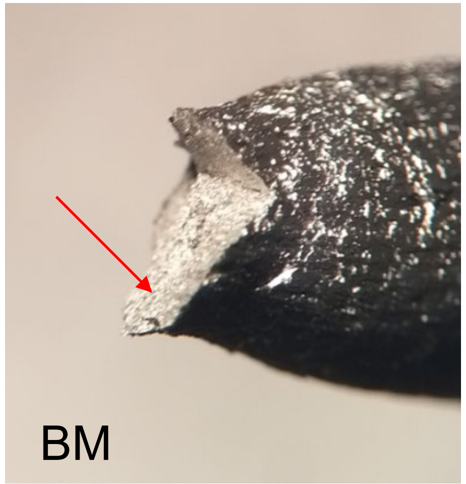


BM

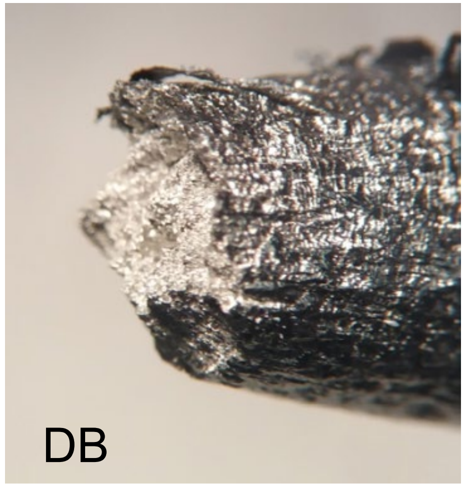
DB 1

DB 2

DB 3



BM

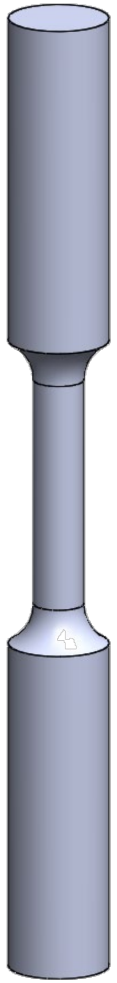


DB 4

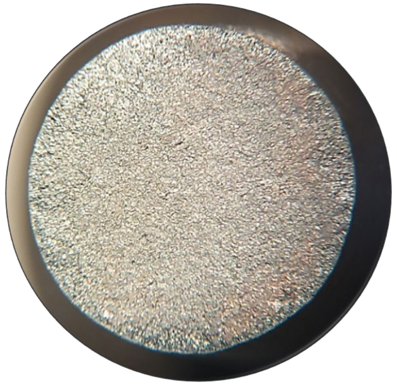
DB 4

Rupture surfaces from tension tests at 760^{o}C

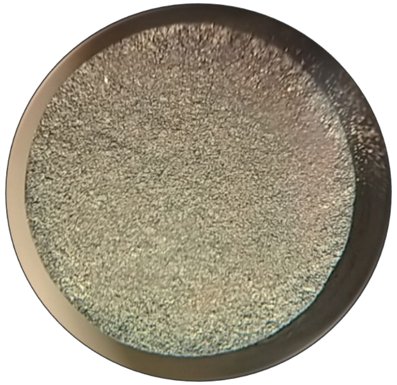
Tasnim Hassan thassan@ncsu.edu
Heramb Mahajan hpmahaja@ncsu.edu



Tension specimen



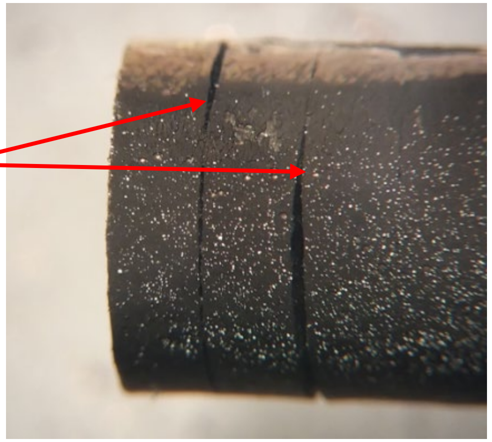
DB_T760_1



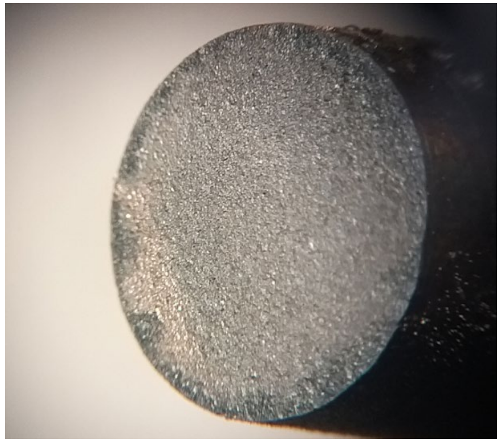
DB_T760_2

DB_T760_3

Delamination of multiple plates



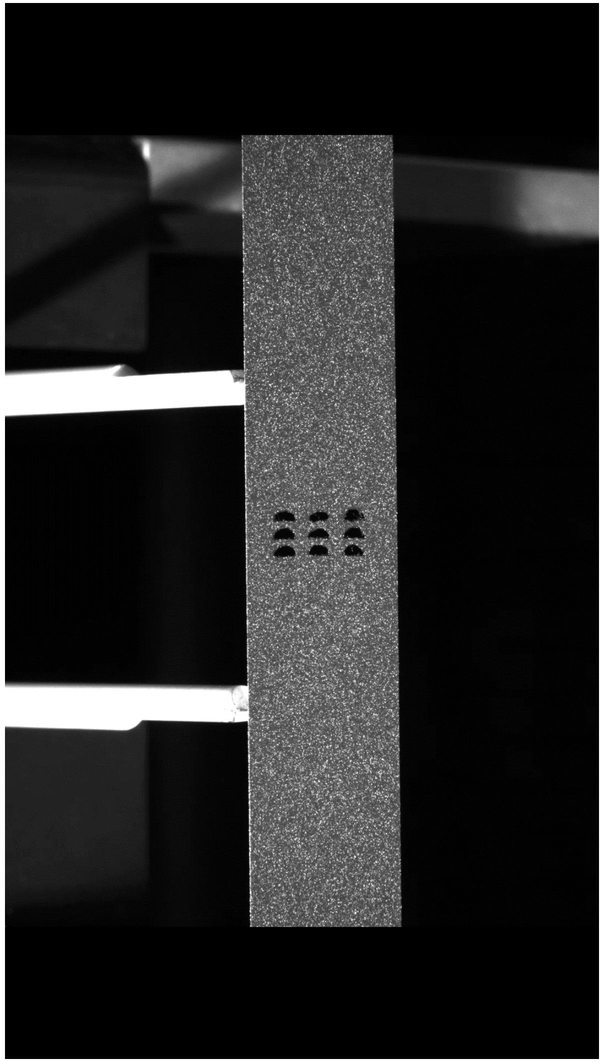
DB_T760_2



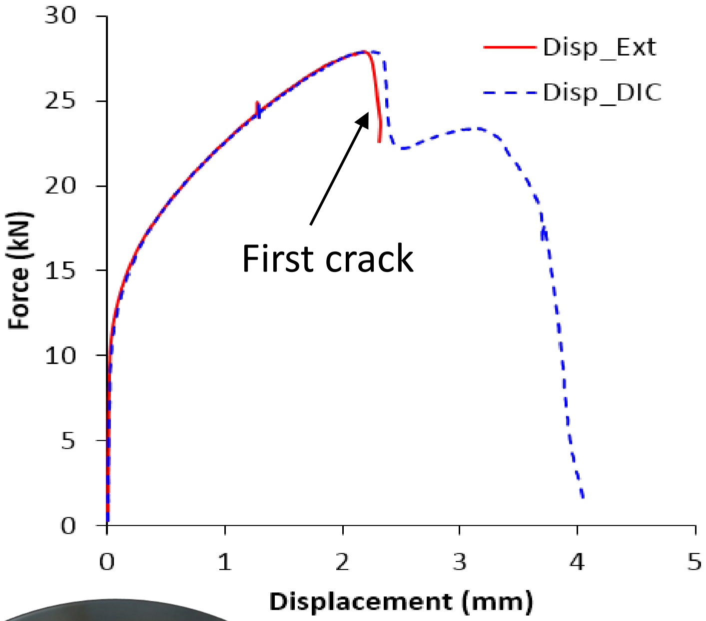
DB_T760_3

Flat channel tension test at RT

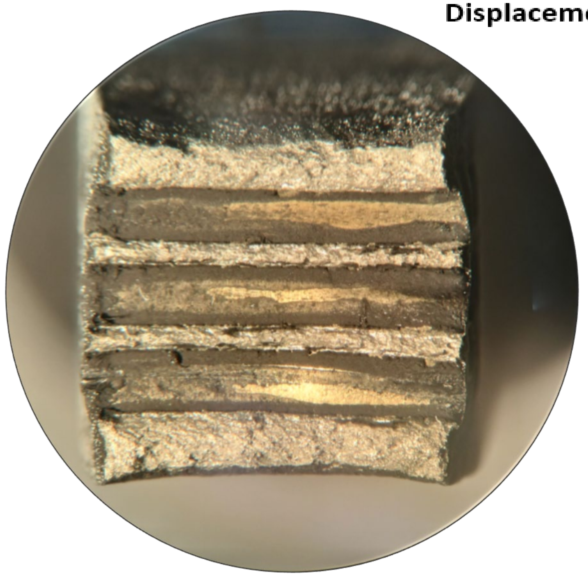
Pretest specimen



After test



BM DB1 DB2 DB3



Material	YS (MPa)	UTS (MPa)	% Elong
800H	260.53	580.28	52.8
DB 1	187.01	527.55	51.2
DB 2	159.76	507.48	55.6
DB 3	177.68	526.83	51.5
DB 4	185.13	530.71	55.1
ASME req.*	170	450	30

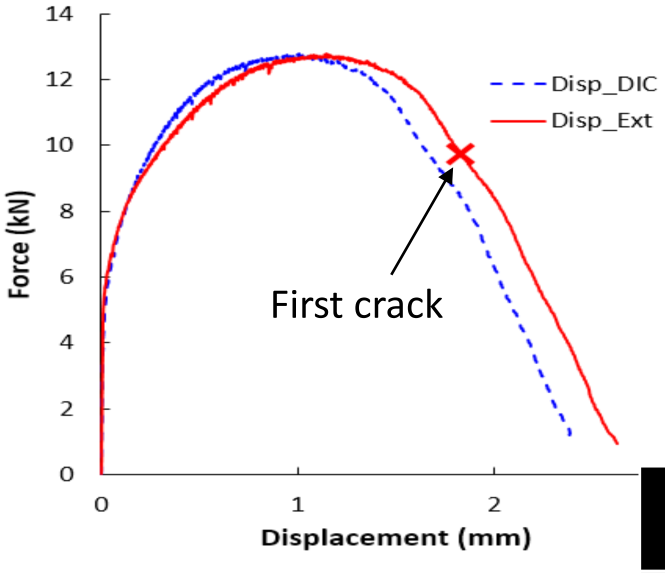
* ASME Sec II Part D, Table 1B, for SB-409, UNS N08810

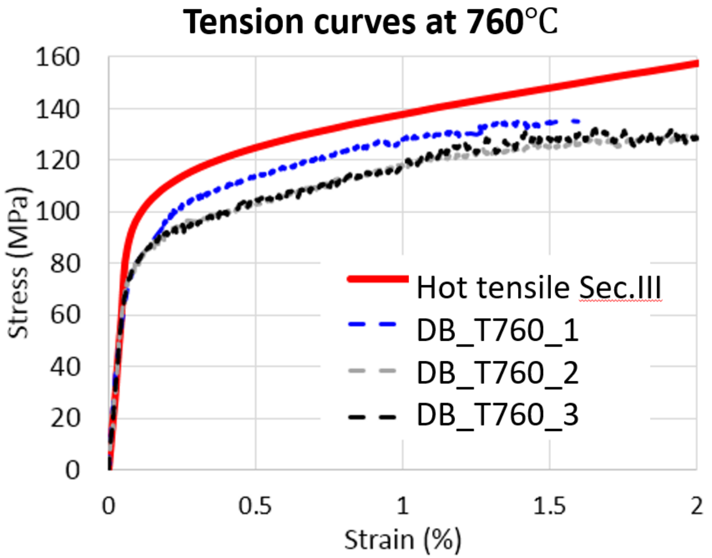
Tasnim Hassan thassan@ncsu.edu
Heramb Mahajan hpmahaja@ncsu.edu

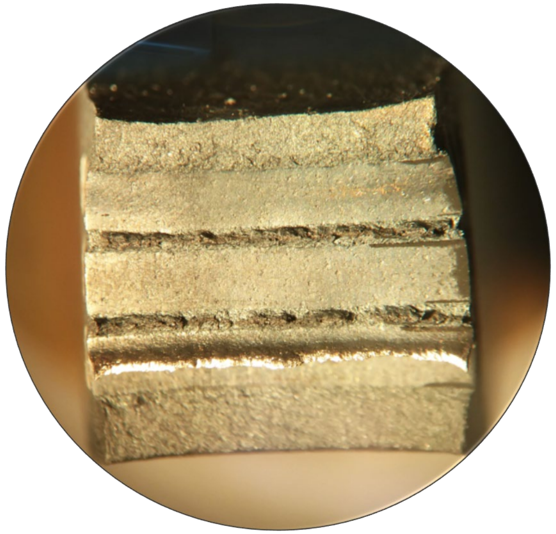
Flat channel tension test at 760℃

Pretest specimen

After tes







Material	E (GPa)	YS (MPa)	UTS (MPa)	% Elong
DB_T760_1	143.7	103.3	163.0	16.0
DB_T760_2	133.1	96.8	144.6	13.9
DB_T760_3	134.6	95.0	153.0	14.8
BM 800H*	151.0	93.8	248.0	

* ASME Sec. III Table HBB-I-14.5 and HBB-3225-1, for UNS N08810

NC STATE UNIVERSITY

Tasnim Hassan thassan@ncsu.edu
Heramb Mahajan hpmahaja@ncsu.edu

Needs going forward

1. **BETTER COSTING MODELS.** This will determine if economic benefits of given type of CHX (regenerator –vs- recuperator)

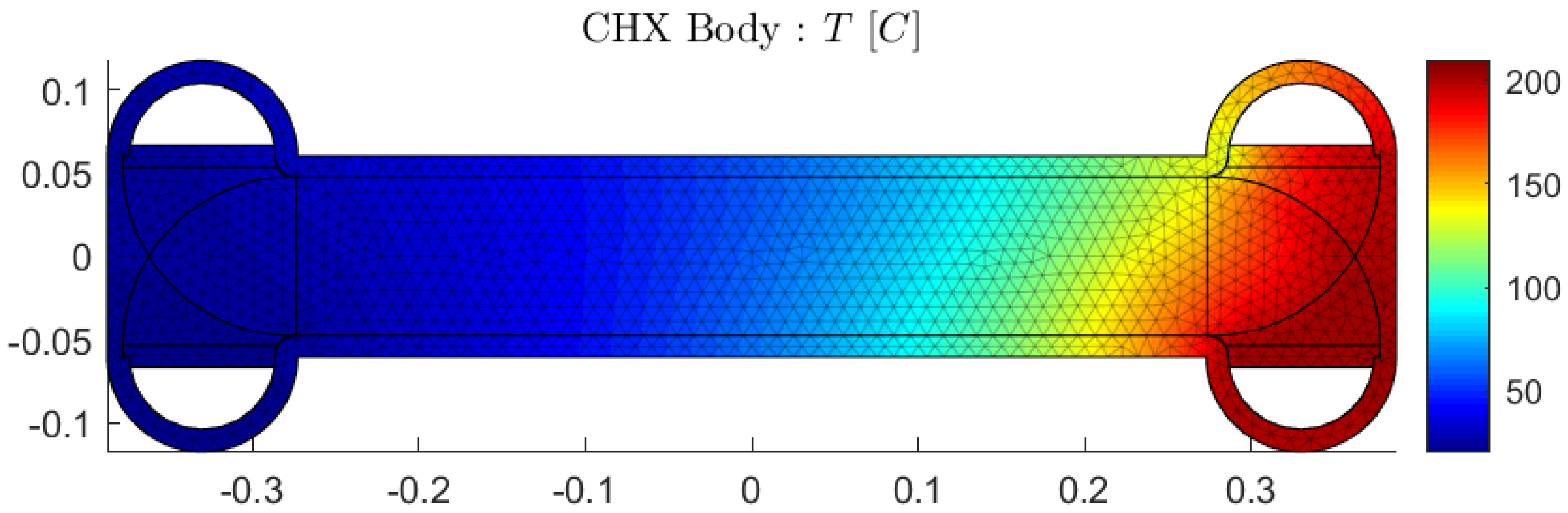
2. **BOND PROPERTIES.** Better understand the performance and limitations of the high temperature recuperator. Specifically there is a lack of properties of the bond layer at high temperature. We need yield, tensile, elongation, creep and creep fatigue resistance of the bond layers at operating temperatures. While it is possible to make diffusion bonded heat exchangers for the higher temperature pressure conditions, we need a better fundamental understanding of the diffusion bond.

3. **EXPERIMENTAL OPERATION AT RELAVENT CONDITIONS.** We need extensive tests of compact heat exchangers with salt, sodium and particles at high temperature - Specifically with respect to clogging (but also flow distribution and effectiveness) for the salt, and for abrasion and lifetime with the particle heat transfer. We need data on performance (heat transfer, ramp rates, draining, restart, freeze, thaw, etc).

4. **SOLAR THERMAL.** the handling of the particles is still a concern for the particle path way. The corrosion of the salt on an industrial scale is an issue with the liquid pathway (i.e., cost of purification to the level needed to run cost allowable materials for piping) issues with leaks and the associated very high corrosion rates if a leak develops.

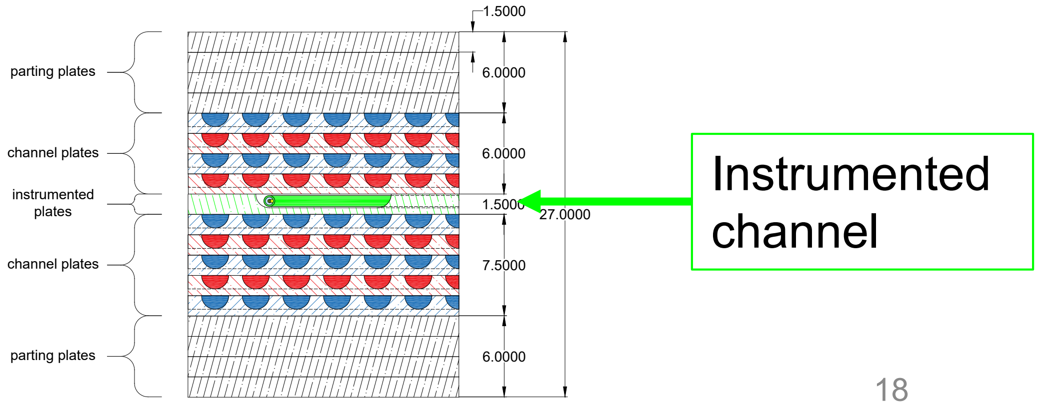
5. **ADVANCED NUCLEAR** – need operational experience – ability to do detailed model calculations, some method of in service inspection, significant data on bond properties – to feed into ASME code case

Solid body temperature lies between hot and cold CO_2

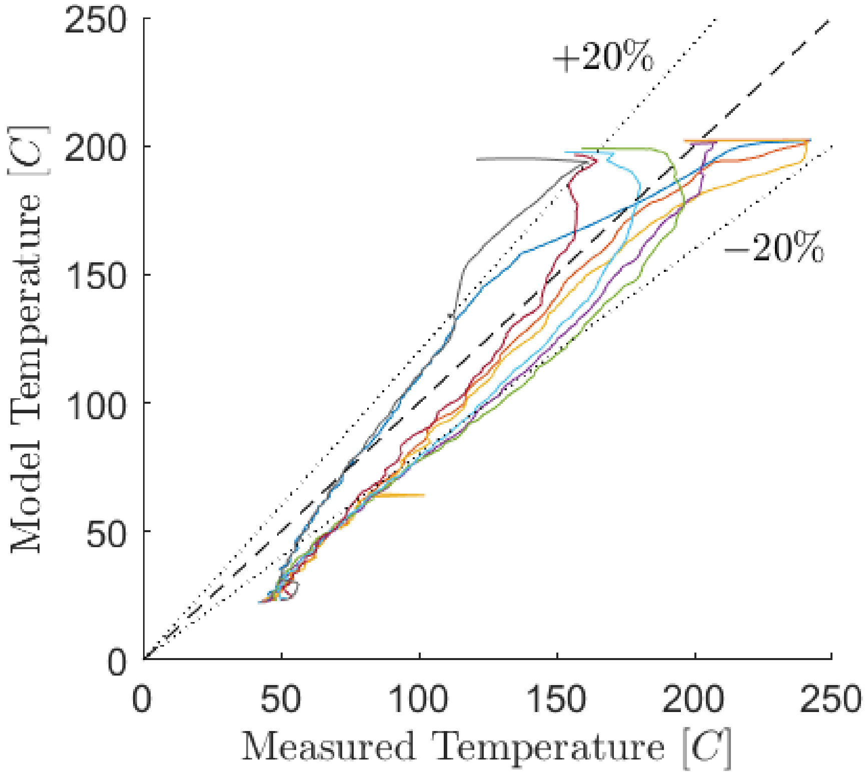


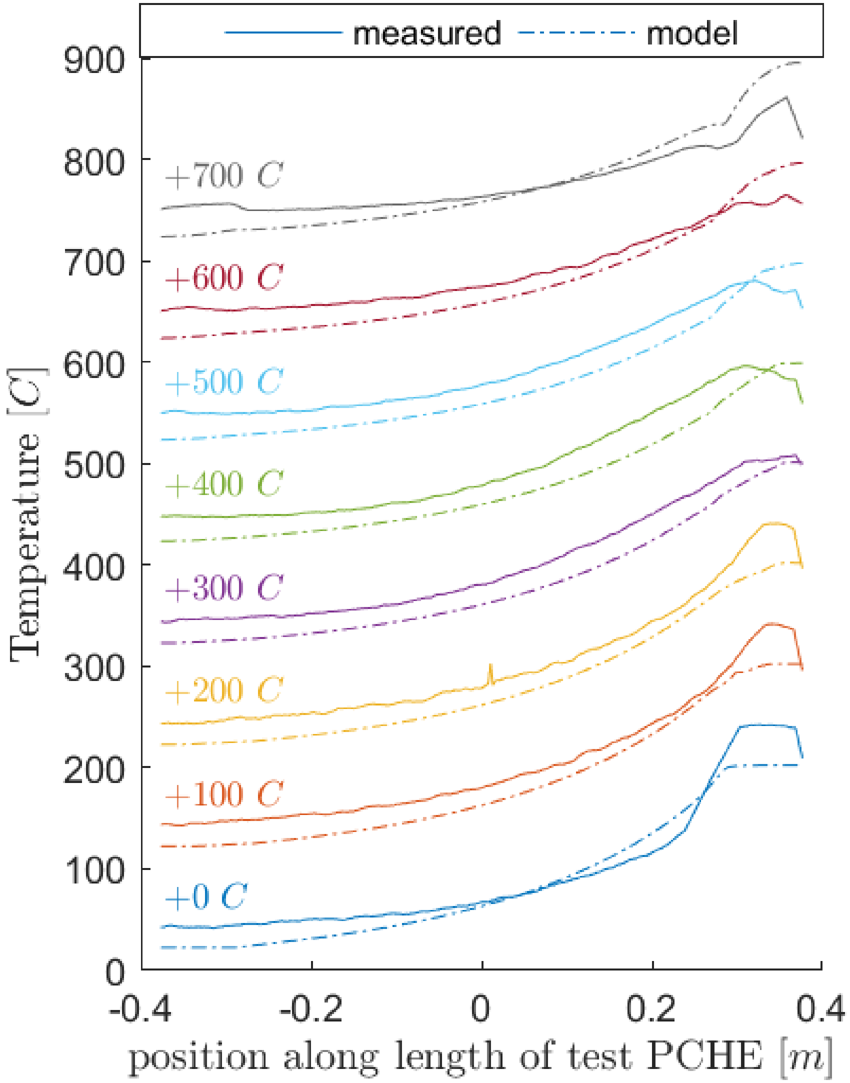
Solid temperatures

- Conduction smoothest out the CO_2 sides' sharper thermal gradients
- Can be compared to experimental measurement of the CHX temperature



Model solid body temperatures are within 20% of experiment

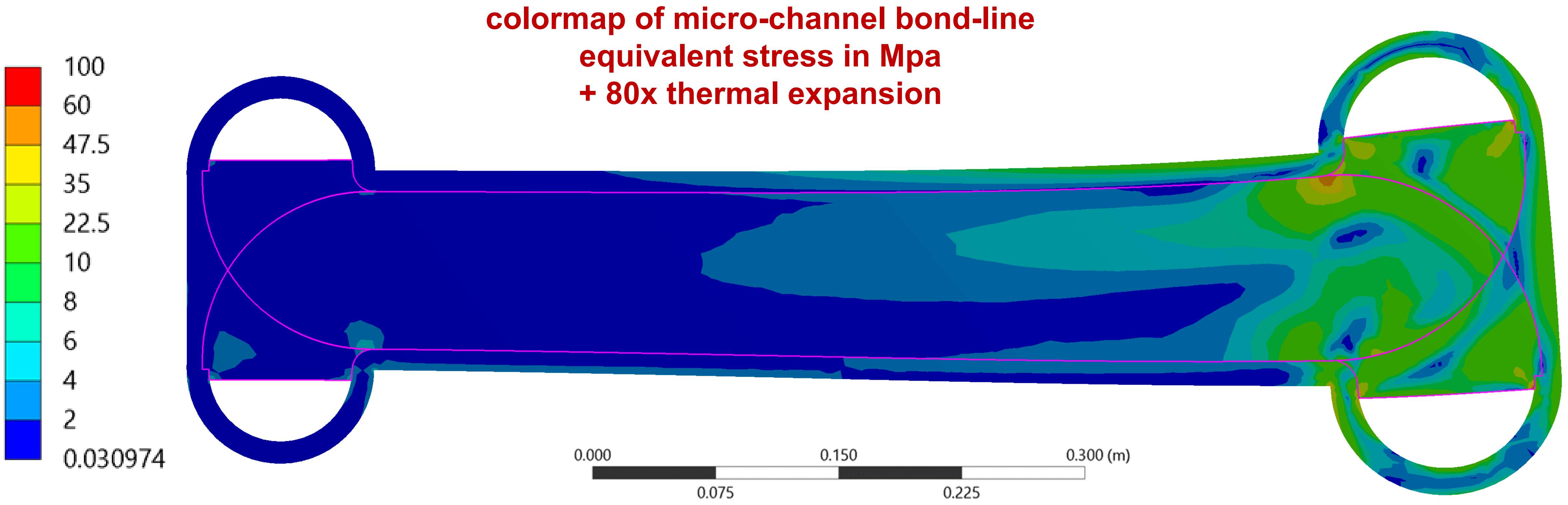




Fiber-optic temperature measurement

- 8 fibers run along length of airfoil PCHE
- Took steady state temperature readings
- Model results along fiber positions compared to actual fiber measurement fall within 20%

Thermal stress on micro-channel bond line



Bond-line stress mapping

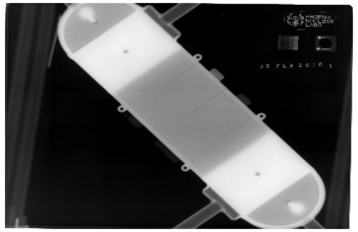
$$\sigma^*_{ij} = K_{ij}\sigma_{ij}$$

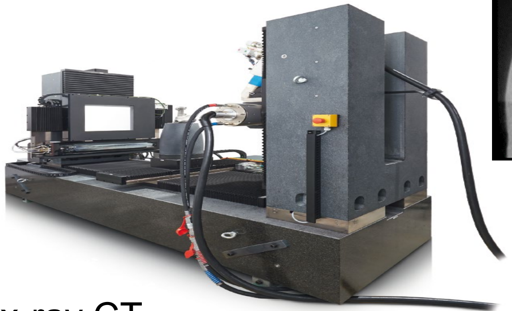
bond-line equivalent stress

$$\sigma^*_{eq} = \sqrt{\frac{\left(\sigma^*_{11}-\sigma^*_{22}\right)^2+\left(\sigma^*_{22}-\sigma^*_{33}\right)^2+\left(\sigma^*_{33}-\sigma^*_{11}\right)^2+6\left({\sigma^*_{12}}^2+{\sigma^*_{23}}^2+{\sigma^*_{31}}^2\right)}{2}}$$

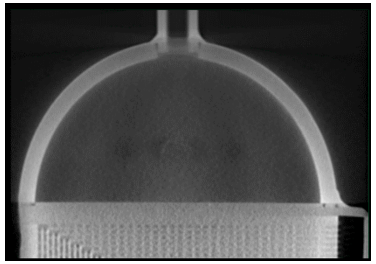
NDE and DE evaluation

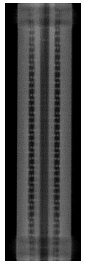
During and after exercising HX

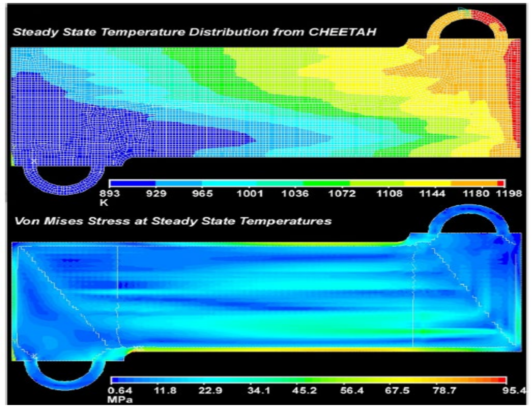




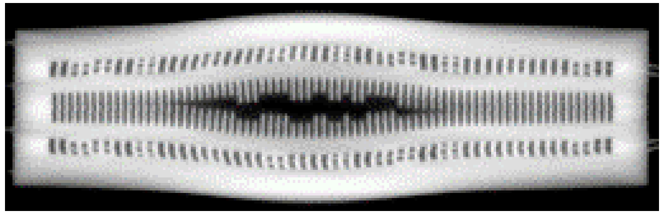
x-ray CT





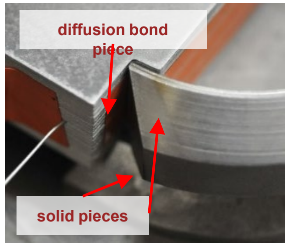


Thermal performance



Destructive testing
-fusion welds
-diffusion welds
-dissimilar materials

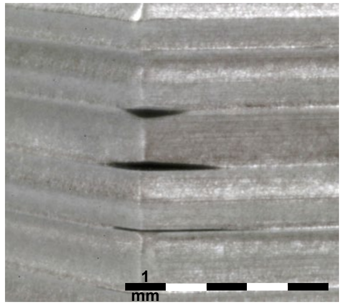
Weld Inspection



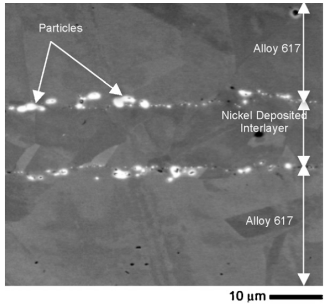
Before welding

Header welds

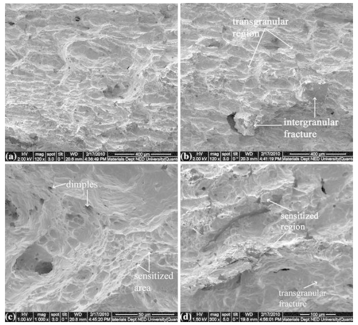
Diffusion Bond Inspection



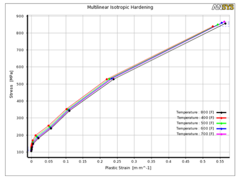
Etch-mask penetration defects



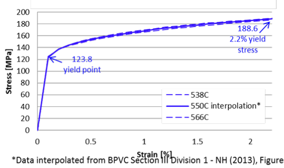
Bond inclusions in alloy 617 [1]



Stress Strain curves derived from Annex 3-D

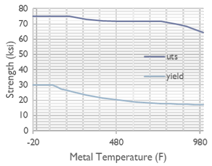


Interpolation of BPVC curves to 550C

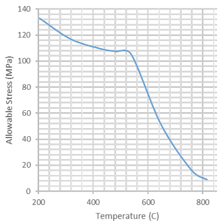


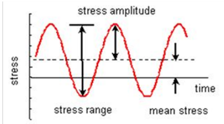
*Data interpolated from BPVC Section III Division 1 - NH (2013), Figures

Strength parameters for 316 SS



BPVC Stress Limit for SS316





Stress Amplitude $S_a = \frac{S_{maximum} - S_{minimum}}{2}$

Mean Stress $S_m = \frac{S_{maximum} + S_{minimum}}{2} \neq 0$

BPVC Cycle Limits for SS316