Heat exchangers, Materials and Application to solar and Nuclear power

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focus on one particular technology gap of sCO2 systems which you think could be resolved or developed further by researchers at university. In other words, the vision of the panel “What Universities can do (or are actually doing) to help make sCO2 a commercial reality?”.

- **heat exchangers/materials and application to nuclear power (i.e., ASME section 3).**

Contributions from: Shaun Aakre, Ian Jentz, Jacob Mahaffey, Jack Hinze, Andrew Brittan, Logan Rapp, Becky Sondelski, Paul Brooks, Bryan Coddington, Greg Nellis

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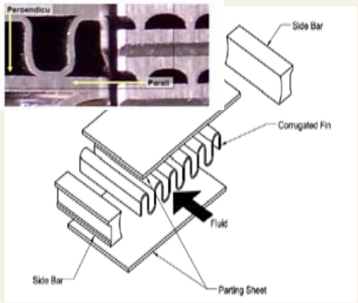
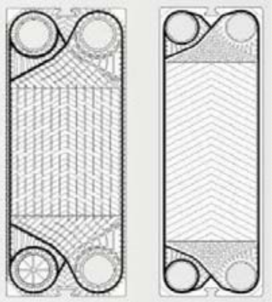
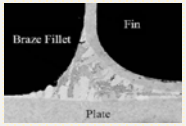
Advanced compact HX for sCO$_2$

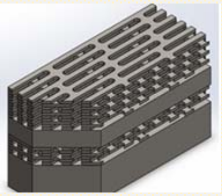
Optimization of HX geometries for f&j

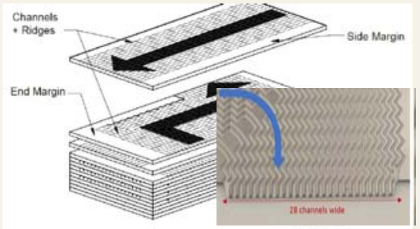
1. Need to qualify for ASME Boiler and Pressure Vessel code. Section III – nuclear service
2. Understand and determine failure mechanisms
3. Optimize for low DP and high effectiveness
4. Reduction in materials and construction costs.



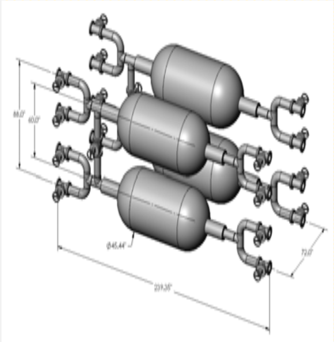


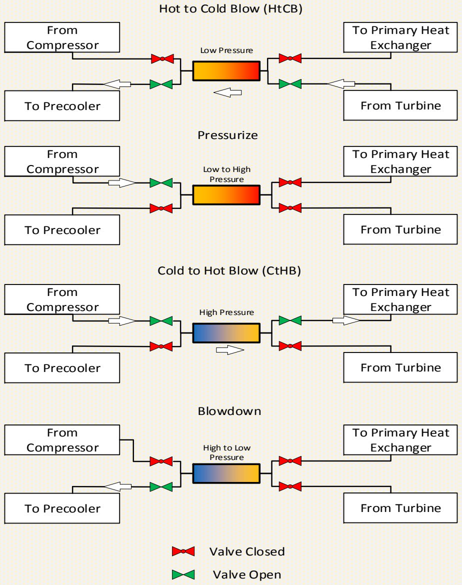






Fixed bed regenerator





Hot to Cold Blow (HtCB)

From Compressor — To Primary Heat Exchanger

Low Pressure

To Precooler — From Turbine

Pressurize

From Compressor — To Primary Heat Exchanger

Low to High Pressure

To Precooler — From Turbine

Cold to Hot Blow (CtHB)

From Compressor — To Primary Heat Exchanger

High Pressure

To Precooler — From Turbine

Blowdown

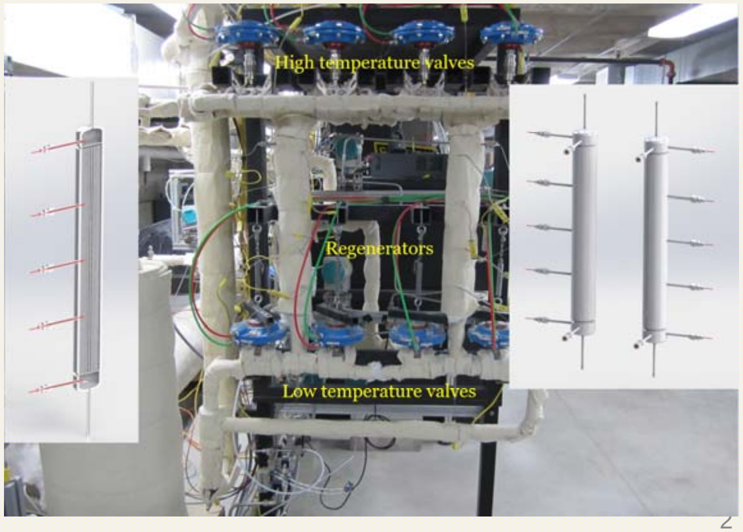
From Compressor — To Primary Heat Exchanger

High to Low Pressure

To Precooler — From Turbine

🟥 Valve Closed

🟩 Valve Open



Section VIII -vs- Section III

VIII - Division 2 (non-Nuclear)

PCHE code case exists

- **The most conservative case for non-nuclear applications**
- **Analysis can be carried out over an entire structure without the need to categorize stresses**
  - Limits are imposed uniformly on all points of stress
- **Plastic collapse**
  - Stress beyond the yield point is allowed as long as plasticity is appropriately modeled.
  - Plasticity models can vary in conservativeness from bilinear to full multilinear implementation of the σ-ε curve
- **Local failure**
  - Limits are imposed on the extent of plastic strain
- **Collapse from buckling**
  - Buckling analysis must be performed on any structures found to be compressively loaded
- **Fatigue failure from cyclic loading**
  - Cyclic loads such as startup/shutdown and load following must be accounted for.
  - Implements cycle limits on periodically varying loads.

Organizations Involved

MPR Associates
CompRex, LLC.
Vacuum Process Engineering
Georgia Institute of Technology
North Carolina State University
University of Idaho
University of Michigan
University of Wisconsin
Electric Power Research Institute
Sandia National Laboratories
Phoenix (Nuclear Laboratory), LLC.

III - Division 1 (Nuclear service)

PCHE code case in progress

- **Required for any Class 1 components. Metallic vessels, heat exchangers, pumps, piping, valves, etc. used in Nuclear power plants.**
- **Stresses found during analysis have to be classified**
  - Different limits are applied based on the stress classification
  - General primary membrane P_m, local primary membrane P_L, primary bending P_b, expansion P_e, secondary Q, peak F.
- **Service level must be specified**
  - Level A is temperatures and conditions below the onset of creep
  - Level B is temperatures where creep occurs; here time limits are imposed based on calculation of creep life
  - Level C is temperatures and conditions supporting ratcheting at extreme fatigue. Cycle limits are imposed.
- **Plasticity**
  - Strain hardening cannot be counted in models. Only simple elastic-perfectly plastic models can be used. This is more conservative than Section VIII.
- **Local Failure**
  - Limits on strain are imposed based on stress classification and service level. Service levels B and C allow substantial strain to account for creep and ratcheting.
- **Buckling**
  - Buckling analysis must be performed on any structures found to be compressively loaded
- **Creep**
  - Creep life of Level B components is evaluated
- **Fatigue and Ratcheting failure from cyclic loading**
  - Fatigue and Ratcheting are considered for Level C components
  - Fatigue excursions with cycle limits < 10^6 cycles are not allowed

Code & Commercialization gaps

Section III PCHE Code Case Gaps	Commercialization Gaps
Stress classification rules (Primary, secondary, peak)	Roadmap to Section III certification
Allowable stress limits in diffusion bonded materials	Creep-fatigue quantification methods
Allowable stress and material properties in weldments	Acceptable thermal ramp rate
Determine if heat treatment is required after bonding	Detection methods of fouling and channel plugging
Suitability of existing welding rules for header attachment	Cleaning methods to mitigate scaling and plugging
Examination methods of weld and diffusion–bonded core	Determine limits for cyclical operation
Modify proof pressure testing procedure if necessary	Estimate regular inspection costs
Provide rules for inelastic analysis methods	Special limitations for reactive coolants
Acceptable plastic strains in flow passage region	Utility and requirement of instrumentation
Creep-fatigue curves for diffusion bonded materials	Identify operational quirks using molten metal or salts
Isochronous stress-strain curves	Platform for testing instrumentation
Identify and mitigate all failure modes	FEA Methodology for Section III certification

Developments on PCHE Code Qualification

2005 – requirements for diffusion-bonded microchannel heat exchangers outlined in Code Case 2437-1.

2009 – Code Case 2621-1 provided design, fabrication, and inspection requirements. Limited to 304L, 316L, and 2205 stainless.

2011 – Diffusion-bonding (diffusion-welding) was added to allowed Section IX welding processes.

2015 – Nestell and Sham publish "ASME Code Considerations for the Compact Heat Exchanger."

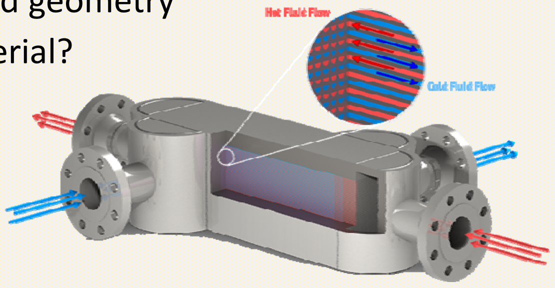
2017 – IRP Grant rewarded for Section III Code Case development

Ongoing – Section III, Division 5 qualification effort of Alloy 617 and 230

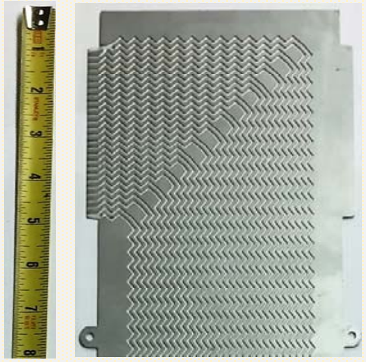
Three investigation strategies:

1) Finite Element Analysis (EPP, Inelastic)
2) Testing of small diffusion-bonded specimen (tensile, creep, creep fatigue)
3) Testing of lab-scale PCHEs using a variety of coolants

Printed-Circuit Heat Exchanger (PCHE)

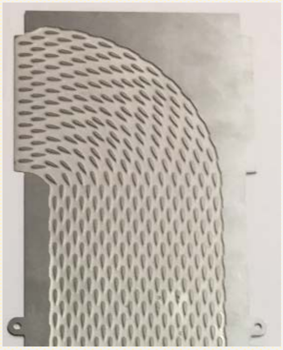


0. **Steady State performance –** obtain Darcy and Colburn factors
    - Are existing flow and heat transfer correlations valid for exotic coolants?
1. **Creep Test –** high temperature, high pressure run for 500+ hours on under-designed geometry
    - Where will maximum creep occur? Are creep properties similar to the base material?
2. **Ratcheting Test –** subject unit to temperature oscillation for ~1000 cycles
    - When and where will ratcheting occur and will it cause shim separation?
3. **Thermal Fatigue Test –** high temperature, moderate pressure
    - Where are cracks most likely to form? How can crack propagation be mitigated?
4. **Thermal Ramp Test –** test a Section VIII design under rapid transients
    - How fast can PCHEs be brought up to temperature? What are the load-following limits?
5. **Fouling/Clogging –** measure accumulation in channels and try cleaning methods
    - How can fouling be measured and mitigated? How does this vary with respect to coolant?



Herringbone (zig-zag)
Geometry

ShimRex
Geometry



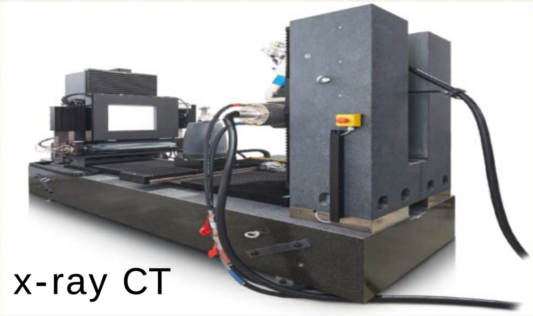
Airfoil-fin Geometry

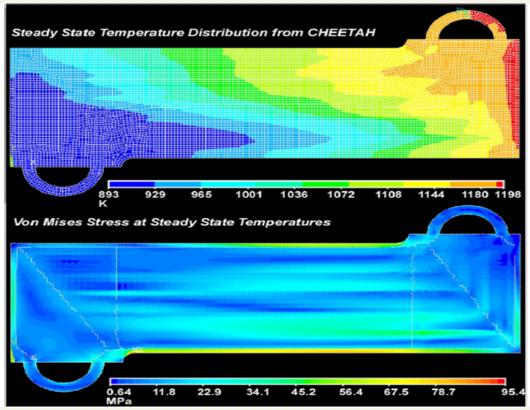
Materials Studied: Alloy 800H and SS316H

The allowable stresses for operation in the creep range are time-dependent and provided in Division 5 for five alloys: **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.

NDE and DE techniques for evaluating CHX

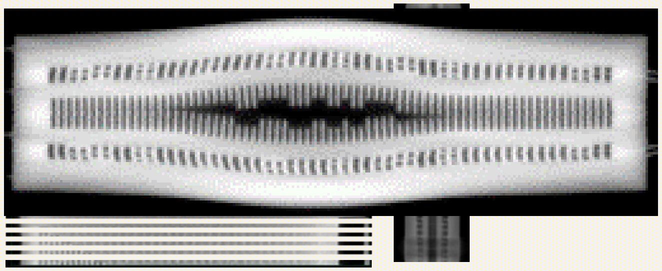

Neutron CT


x-ray CT

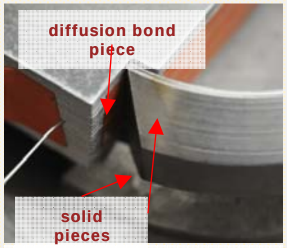


Thermal performance

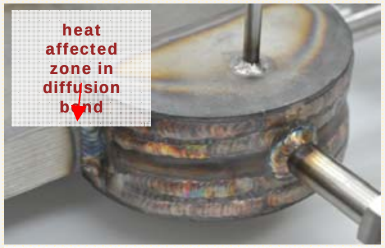

Ultrasonic inspection



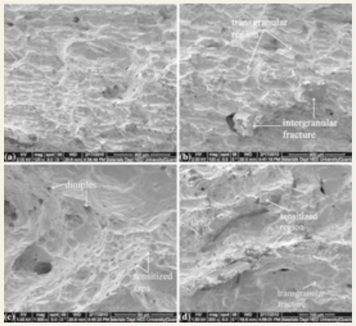
Weld Inspection



Before welding

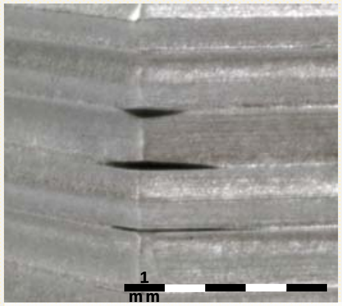


Header welds

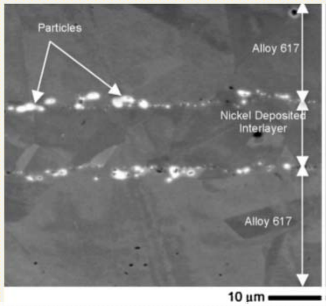


Destructive testing
- fusion welds
- diffusion welds
- dissimilar materials

Diffusion Bond Inspection

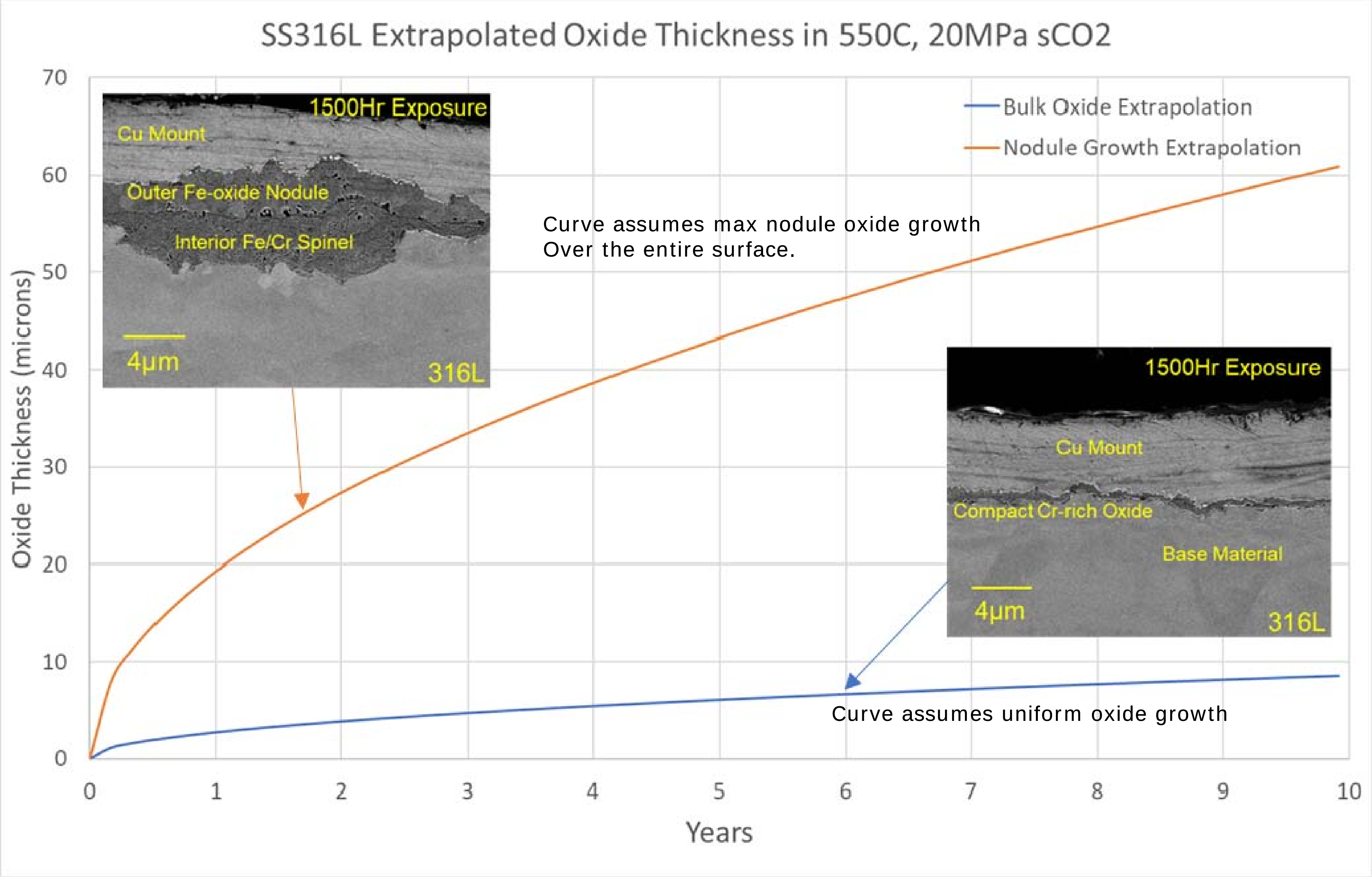


Etch-mask penetration defects



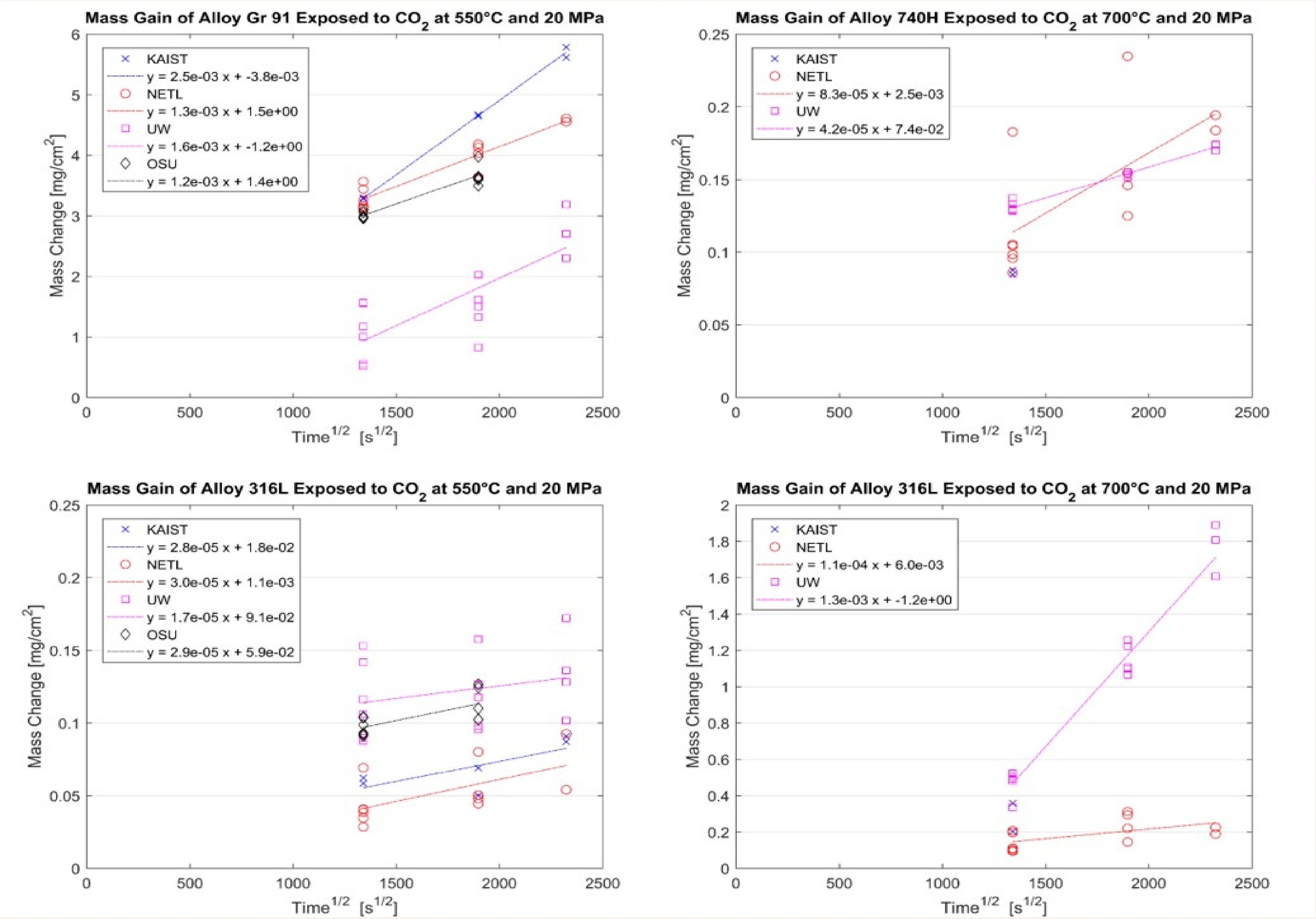
Bond inclusions in alloy 617 [1]

Assessment of pipe/component corrosion allowance



Curve assumes max nodule oxide growth
Over the entire surface.

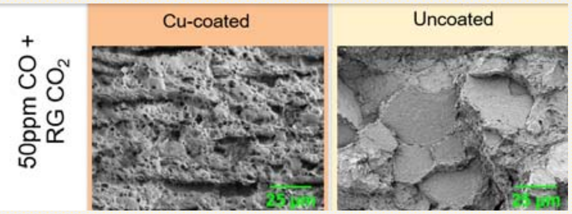
Curve assumes uniform oxide growth



Paper 146 Tucker, et al 2018, sCO2 symposium (ROUND ROBIN TESTS at multiple institutions)

Thursday 10:15

Evaluation of materials, Pipe welds, dissimilar materials welds, mechanical, tensile, corrosion rates, impurities



	UTS (MPa)	0.2% YS (MPa)	Elongation (%)
316L: Unexposed	**605 ± 1**	**297 ± 3**	**81.2 ± 1.2**
316L: 750°C CO_2	598 ± 15	220 ± 1	26.8 ± 4.7
316L: 750°C CO_2 + 50ppm CO	498 ± 14	291 ± 34	7.5 ± 1.7
316L Cu: 750°C CO_2	590 ± 18	233 ± 12	29.1 ± 11.0
316L Cu: 750°C CO_2 + 50ppm CO	641 ± 4	263 ± 4	68.7 ± 4.2
316L-316L: Unexposed	**541 ± 5**	**278 ± 2**	**41.2 ± 0.8**
316L-316L: 750°C CO_2	586 ± 11	240 ± 13	19.2 ± 0.4
316L-316L: 750°C CO_2 + 50ppm CO	538 ± 2	252 ± 1	14.3 ± 0.5
316L-316L Cu: 750°C CO_2	581 ± 21	237 ± 6	21.9 ± 5.4
316L-316L Cu: 750°C CO_2 + 50ppm CO	651 ± 15	256 ± 4.9	40.1 ± 4.3

Alloy	Oxidation Notes	Oxide Thickness* [microns/1000hr]	Susceptibility to Impurities Corrosion
T92	Outer Fe rich oxide Inner Fe,Cr rich oxide Spallation observed at 550C	450C – 6.8 550C – 20.3	NA
T122	Outer Fe rich oxide Inner Fe,Cr rich oxide Spallation observed at 550C	450C – 6.4 550C – 1.8	NA
347	Outer Fe rich oxide Inner Cr rich oxide Spallation observed at 650/750C	450C – .2 550C – 1.6 650C – .2 750C – 5.2	Oxygen rich environments accelerate oxidation/spallation
316	Cr rich oxide Fe rich nodules with inner Fe,Cr oxide Spallation observed at 650/700C	450C – .2 550C – .7 650C – 5.9 700C – 5.8	NA
310	Cr rich oxide	450C – .2 550C – .3 650C – .7 750C – 1.1	NA
709	Cr rich oxide	650C – .7	NA
800	Cr rich oxide	450C – .1 550C – .4 650C – .8	Oxygen rich environments severely increase oxidation
718	Cr rich oxide Nodules of Fe rich oxide at T=750C Ti/Al internal oxidation	450C – .1 550C – .6 650C – .8 750C – 1.9	Oxygen rich environments accelerate oxidation/spallation
625	Cr rich oxide	450C – .1 550C – .3 650C – .3 700C – 1.1 750C – 1.7	Oxygen environments enhanced oxidation CO environments enhanced oxidation and caused oxide buckling
282	Cr rich oxide Ti/Al internal oxidation Some oxide cracking	650C – .9 750C – 2.9	Poor resistance to oxygen rich environments Excellent resistance to CO rich environments
617	Cr rich oxide Ti/Al internal oxidation	450C – .1 550C – .3 650C – 1.2 750C – 1.7	Good resistance to oxygen rich environments NA
740	Cr rich oxide Cr/Ti rich nodules oxide nodules Ti/Al internal oxidation	650C – .5 700C – .9 750C – 1.7	Good resistance to oxygen rich environments NA
230	Cr rich oxide	450C – .1 550C – .3 650C – .3 750C – .7	Excellent resistance to impurities corrosion

*Oxide thickness is converted from mass to thickness using density of chromium (spallation and nodule formation can alter these measurements slightly) ~ Estimates are 20 ± 9% accurate based on SEM imaging of 5 different alloys

This table is based on Research Grade (99.999%) CO_2 with impurities consisting of 100ppm O_2 and 1%CO additions

- Universities have a lot of resources – facilities, labor, creative ideas.
- Every project that is done in this area is a collaboration between multiple universities, laboratories, companies.
- Universities are great at disseminating information and building collaborations.

Summary of papers at conference

- **45** Mechanical and Corrosion Performance of the Weld of 740H and 282, Andrew Brittan, University of Wisconsin, Madison
- **59** Switched Bed Regenerators for sCO2 Cycles, Jack Hinze, University of Wisconsin, Madison
- **114** Nuclear Code Case Development of Printed-Circuit Heat Exchangers with Thermal and Mechanical Performance Testing ,Shaun Aakre, University of Wisconsin, Madison
- **130** Thermal-Hydraulic Performance of Compact Diffusion Bonded Heat Exchanger Geometries Using Supercritical Carbon Dioxide as the Working Fluid, Sandeep R. Pidaparti, Georgia Institute of Technology
- **144** Supercritical Brayton Power Conversion with a Direct Cooled Reactor for Space Power, Becky Sondelski, University of Wisconsin, Madison
- **148** Processing and Properties of Robust Ceramic/Metal Composites for Heat Exchangers Operating at >750°C with Supercritical CO2, Kenneth Sandhage, Purdue University
- **146** Supercritical CO2 Round Robin Test Program, Julie Tucker, Oregon State University

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