# Performance modeling and testing for nuclear code case development of compact heat exchangers

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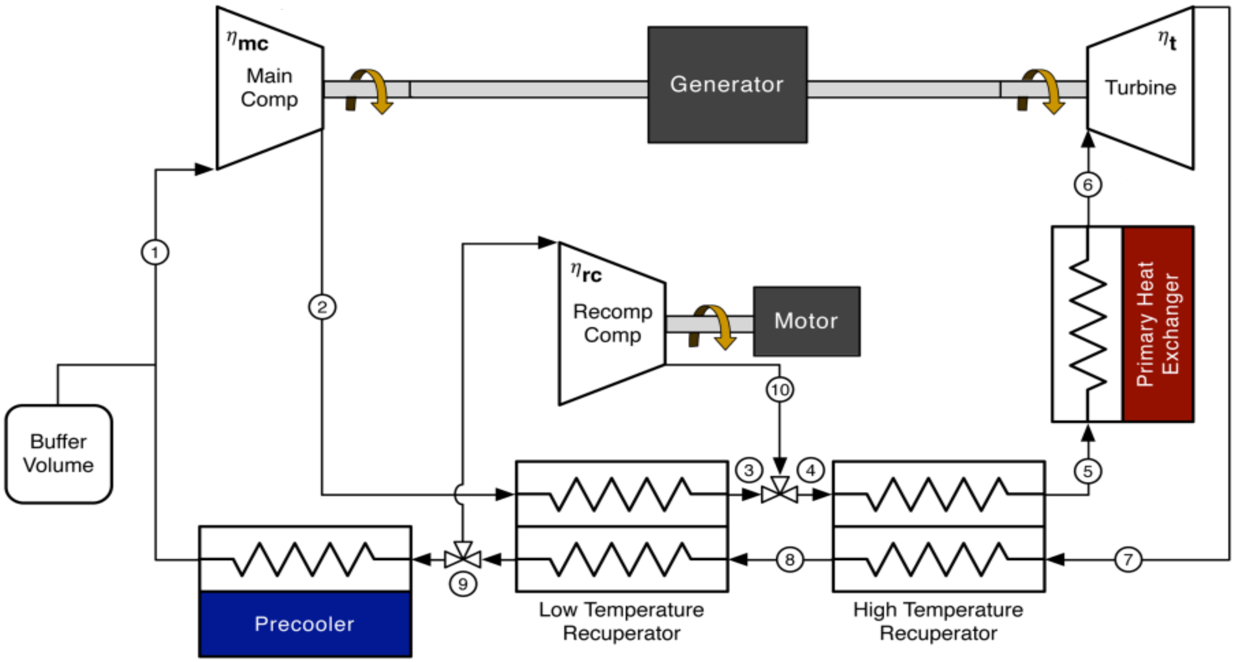
# Presentation Outline

- Motivation
- Project Introduction
- Code qualification procedure
- Experimental plan and facilities
- FEA Methodology
- Internal inspection of PCHEs
- Destructive testing
- Conclusions

# $CO_2$ Cycle Development Motivation




Supercritical $CO_2$ power cycles has been considered a great fit for advanced nuclear reactors for many decades.

**What needs to be done to make this happen?**

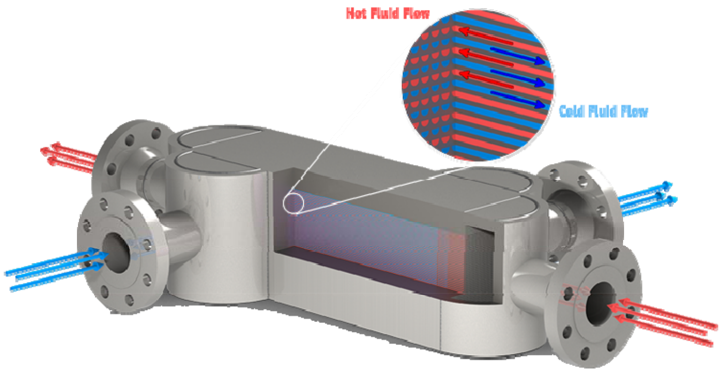
## Some Advantages

- Increased thermal efficiency
  - 50% versus 32-36% of Rankine cycles
- Compact turbine and equipment
  - Reduced capital cost
- Minimal water requirement
  - Ideal for arid regions

## Technical Challenges

- Turbomachinery
- Primary and Intermediate HXers
  - Performance at high temperatures
  - Load flexibility & longevity
  - Dominant failure mechanisms

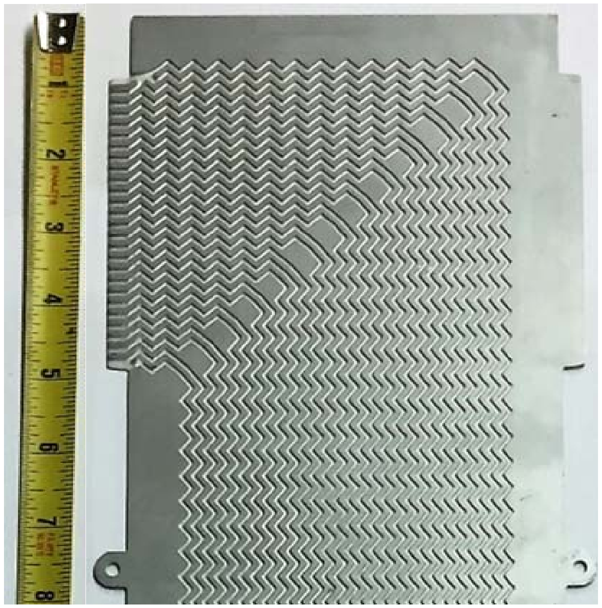
# Printed-Circuit Heat Exchanger (PCHE)




Technical Advantages:

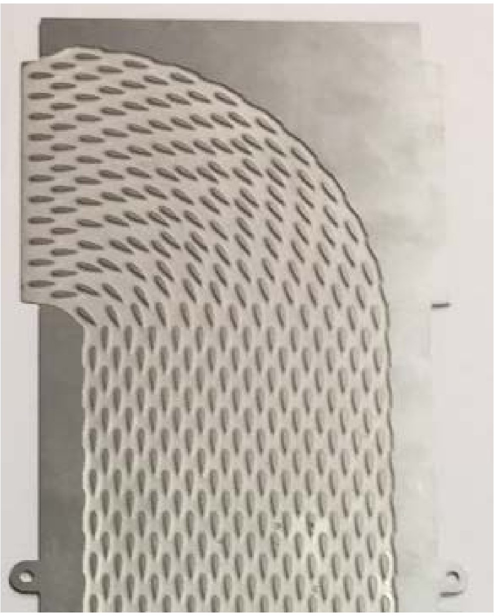
- High effectiveness (approaching 99%)
- Operable at high pressure and high temperature
- High surface area to volume ratio (potential cost-reductions)
- **Open the door for advanced (Gen IV) nuclear reactors using $CO_2$ power cycles**

**Materials Studied:** Alloy 800H and SS316H



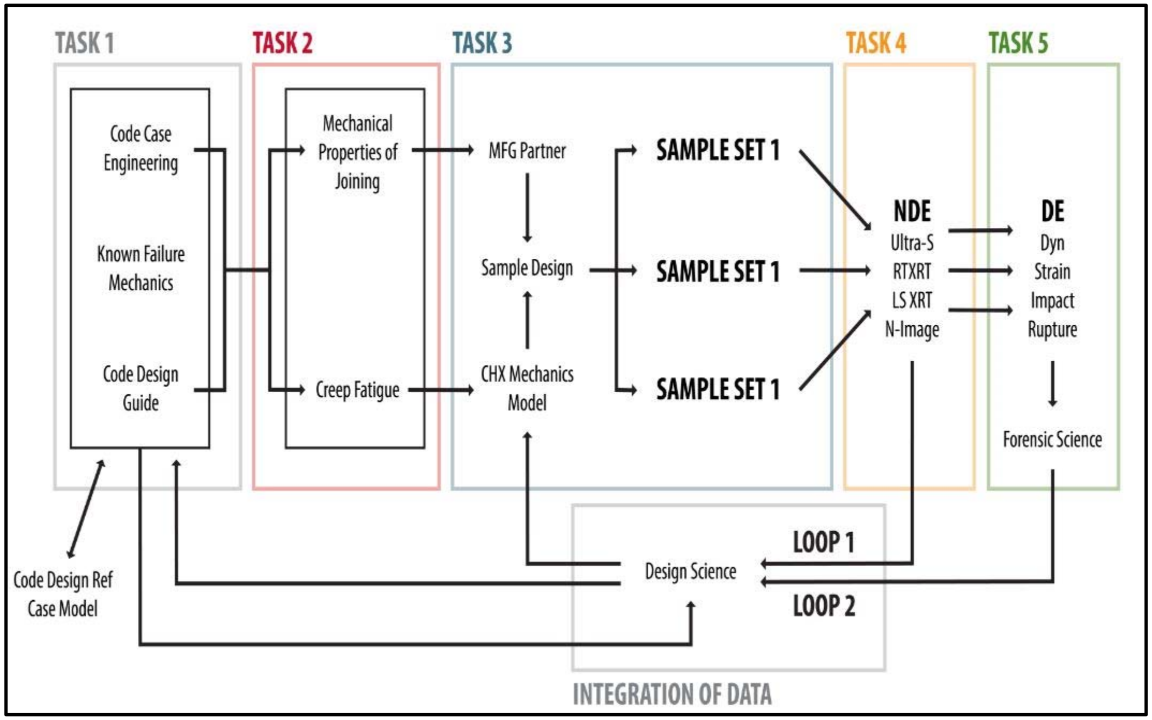
Herringbone (zig-zag) Geometry

ShimRex Geometry



Airfoil-fin Geometry

# Integrated Research Project (IRP)




## Involved Organizations

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.

**Goal:** develop a Section III Code Case for printed-circuit heat exchangers while closing commercialization gaps related to nuclear and non-nuclear (CSP, Oxy-combustion) applications.

Step 1: Identify technical gaps in Section VIII Code Case (# 2621-1) “modified” for Section III
Step 2: Devise tests to fill these technical gaps while solving commmercialization challenges
Step 3: Test diffusion-bonded samples and operational PCHEs with various coolants
Step 4: Compare experimental data with finite element models….. Repeat.

# Section VIII vs. Section III Certification

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## 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.

## 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

WISCO2

| 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

**3) Testing of lab-scale PCHEs using a variety of coolants**

# Planned Testing

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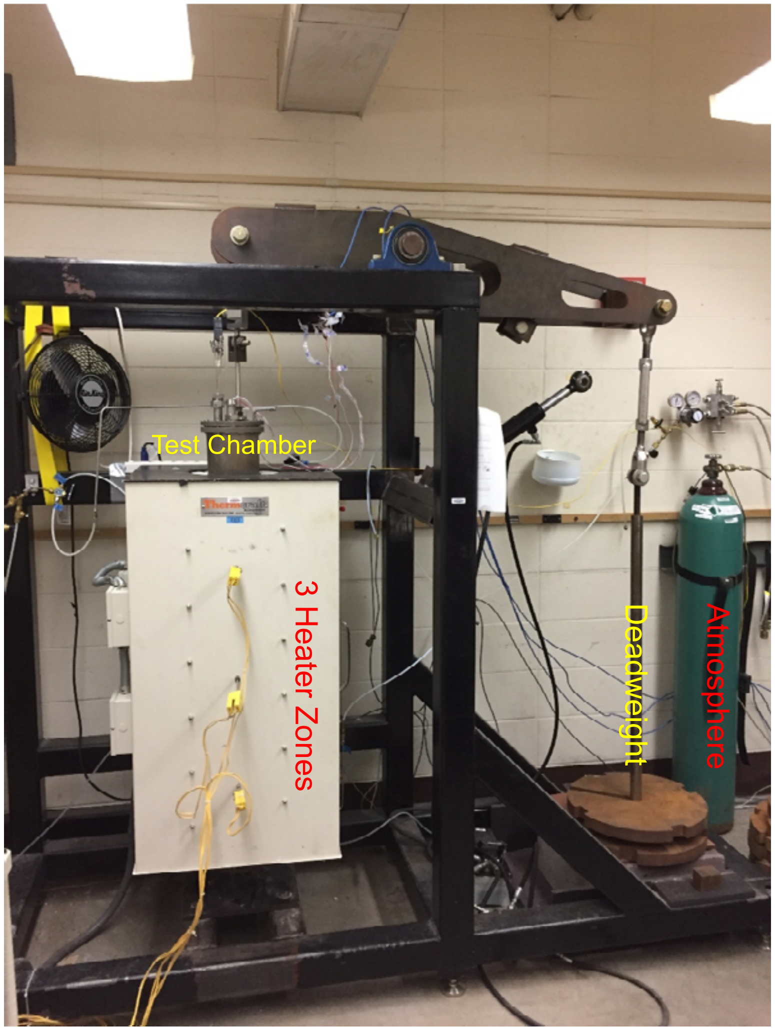
0. **Steady State performance** – obtain Darcy and Colburn factors
   - Are existing flow and heat transfer correlations valid for exotic coolants?
1. **Creep Test** – high temperature, high pressure run for 500+ hours on under-designed geometry
   - Where will maximum creep occur? Are creep properties 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?

Two Geometries
- ShimRex or Marbond
- Herringbone

Two Materials
- Alloy 800H (2018)
- SS316H (2019)

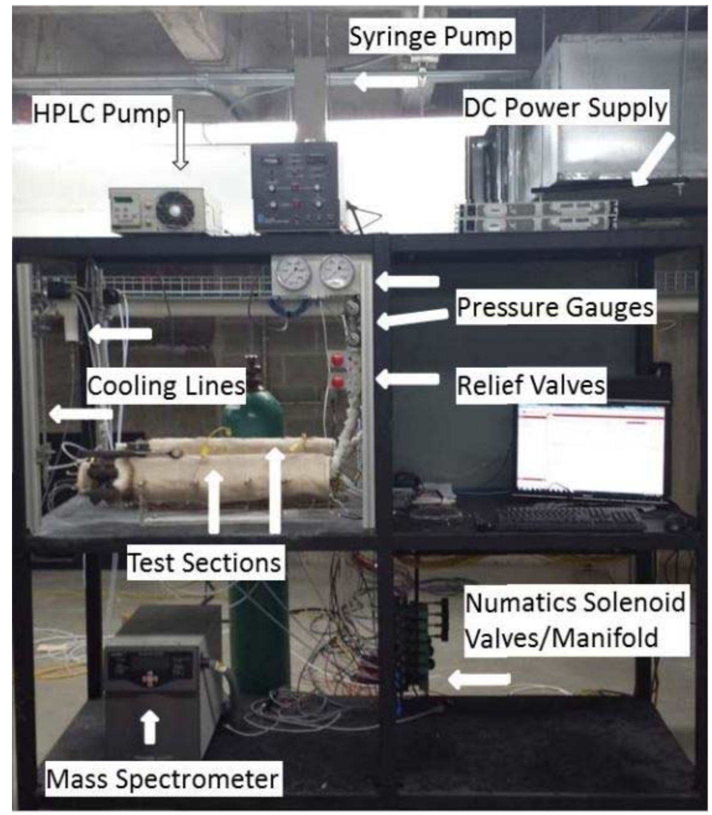
| Institution | Heat Transfer Fluids | Test |
|---|---|---|
| Georgia Institute of Technology | $CO_2$ and Helium | 0, 2, 3, 4, 5 |
| University of Idaho | Air, Water, $CO_2$ | 0, 5 |
| University of Michigan | FLiNaK, $CO_2$, Helium | 0, 1, 4, 5 |
| University of Wisconsin | Sodium, Nitrate Salt, $CO_2$, Air | 0, 1, 2, 3, 4, 5 |

# Sample Corrosion and Creep Testing Facilities




| Deadweight Creep Test Facility | |
|---|---|
| Max Tensile Load | 5000 lb. |
| Max Temperature | 1200° C |
| Max Pressure | 300 psi |

| Corrosion Testing Facility | |
|---|---|
| Autoclave Material | IN 625 |
| Max Temperature | 750 ± 1° C |
| Max Pressure | 3000 ± 2 psi |
| Mass Flow Rate | 0.1 kg/hr |
| # of Autoclaves | 5 on 3 systems |
| Mass Spectrometer | ± 5 ppm |
| Gas Chromatograph | ± 2.5 ppb |



# Sodium and Nitrate Salt Facilities

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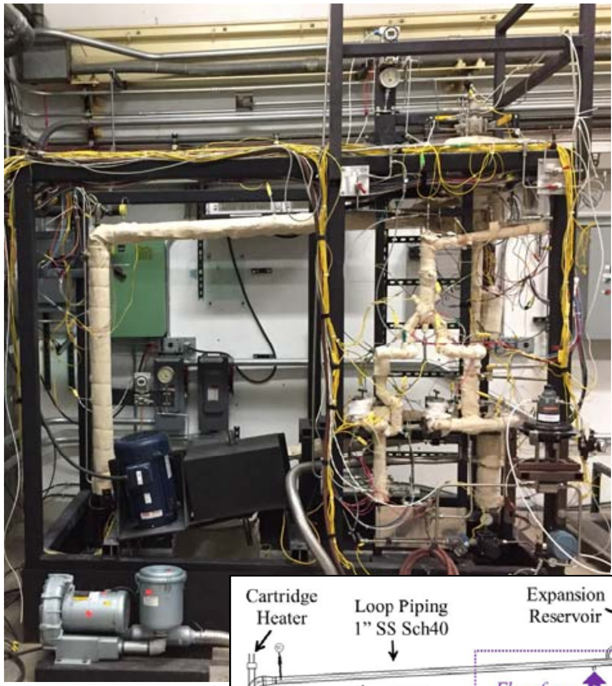
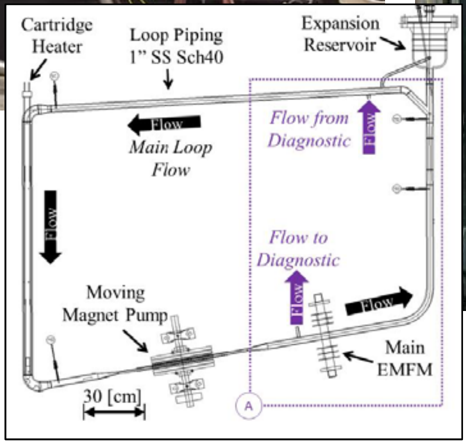




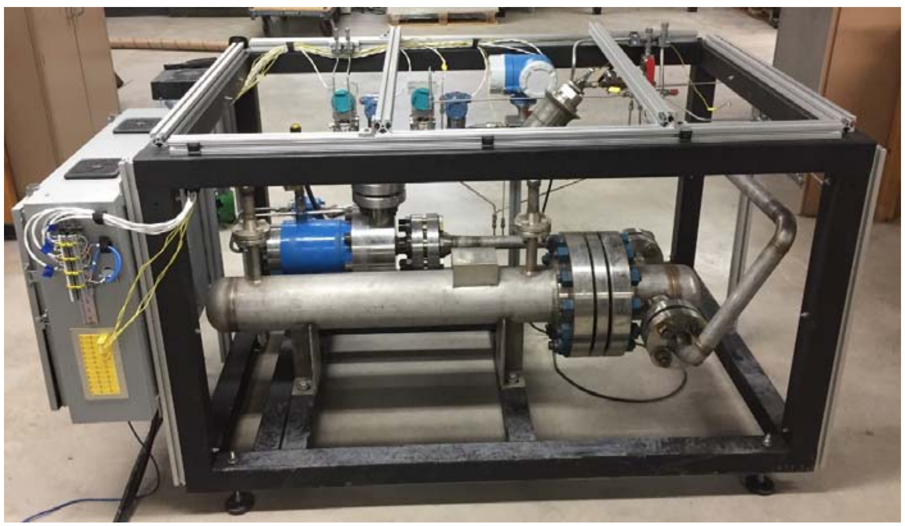


| Salt Loop Parameter | Value |
|---|---|
| Construction Material | 316 Stainless Steel |
| Salt Coolant | 0.6 $NaNO_3$ – 0.4 $KNO_3$ |
| Pipe Size | 2" NPS w/ Grayloks |
| Maximum flow rate | 600 L/min (160 GPM) |
| Salt Pump Head | 17.4 m (57 ft) |
| Heater Power | 20 kW |
| Air Supply | 250 psi @ 150 CFM |

| Sodium Loop Parameter | Value |
|---|---|
| Construction Material | 316 Stainless Steel |
| Temp Range | 100-700°C |
| Sodium Volume | 7 L |
| Maximum flow rate | 150 L/min (40 GPM) |
| Heater Power | 5 kW |
| EM Pump | 24 permanent SmCo magnets |
| Max Pressure Drop | ~ 20 psi |
| Oxide Control | 0.82 L Cold Trap |

# $CO_2$ Testing Facilities


High DP HydroPac supercritical $CO_2$ loop. Used for heat exchanger, component, and systems testing.

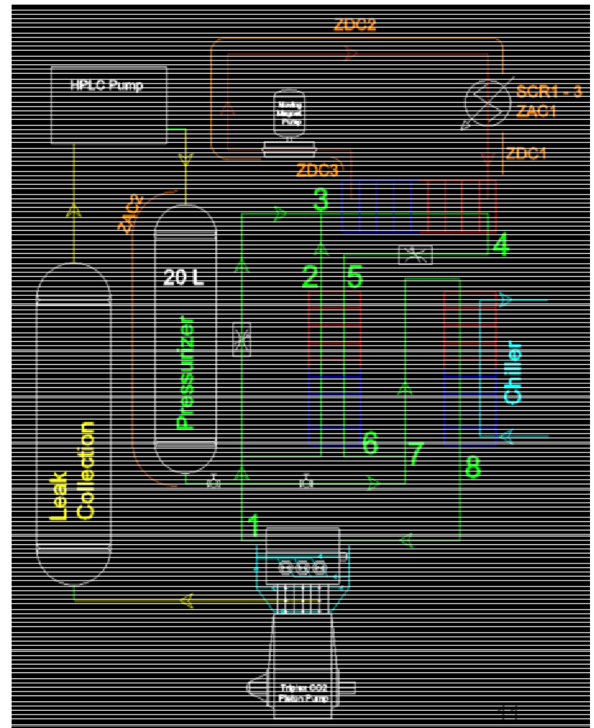


Low DP ChemPump supercritical CO2 loop for testing

| High DP Loop | Value |
|---|---|
| Construction Material | SS316L |
| Max $sCO_2$ Temp | 650°C |
| Max $sCO_2$ Pressure | 25 MPa (3600 psi) |
| Maximum flow rate | 1.6 kg/s |
| Salt Heater Power | 12 kW |
| Cartridge Heater Power | 6 kW |
| Compressor Power | 37.3 kW (50 hp) |

| Low DP Loop | Value |
|---|---|
| Construction Material | SS316L |
| Max $sCO_2$ Temp | 650°C |
| Max $sCO_2$ Pressure | 8 MPa (1200 psi) |
| Maximum flow rate | 1.5 kg/s |
| Max pressure drop | 45 psi |
| Power | 4.18kW (5 hp) |

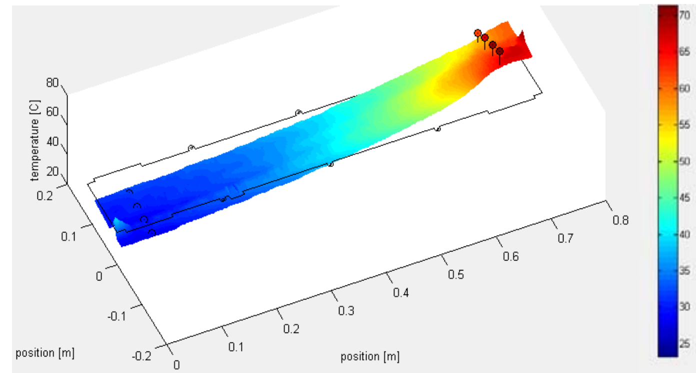
| Triplex Pump | Value |
|---|---|
| Max $sCO_2$ Pressure | 30 MPa (4350 psi) |
| Flow rate range | 0.9 kg/s |
| Power | 30 kW (40.2 hp) |
| # cooling circuits | 5 |



# Instrumentation and Methodology

- Coriolis or venture-style flow meters
- Absolute and differential pressure
- Thermocouples
- Temperature-sensing fibers
- Strain-sensing fibers
- Digital image correlation

PCHE with capillary tube for temperature sensing fibers

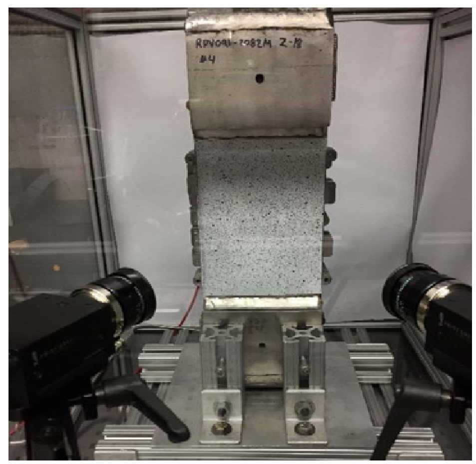



Plot of interpolated temperature data from optical fiber

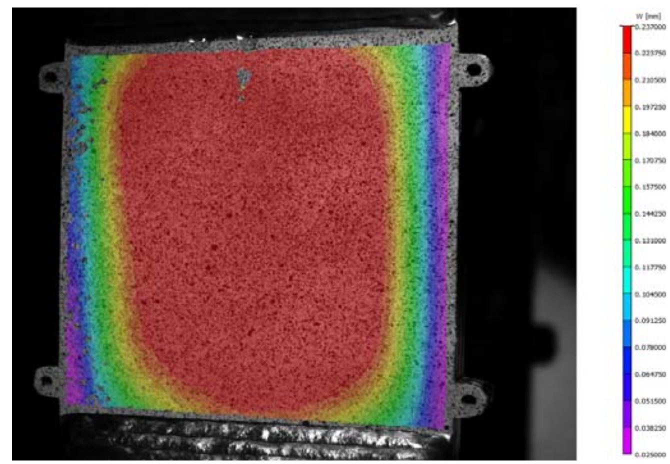
<u>Non-dimensionalized parameters</u>

$$\Delta P = f \frac{L}{D_h} \frac{1}{2} \rho v^2$$

$$j = \frac{h\, Pr^{2/3} A_C}{C_p\, \dot{m}} = \frac{(UA) A_C}{A_s} \frac{Pr^{2/3}}{C_p\, \dot{m}}$$



Hydrotest setup with cameras set for 3-D digital image correlation (DIC)



Displacement contour from DIC data

# PCHE geometry is considered at multiple scales

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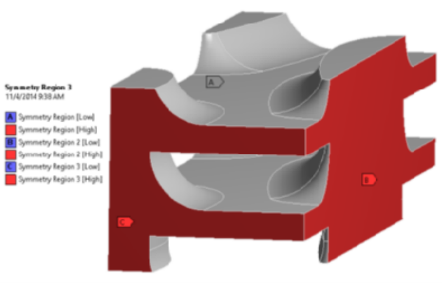
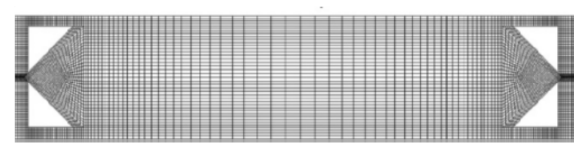
**Local Scale** | **Cross Section Scale** | **Heat Exchanger Scale**





complexity

- Highly Detailed Interior Geometry
  - Etched features are fully resolved
  - High fidelity mesh at diffusion bond and stress concentrations
- Useful for pressure loads and between-channel thermal loads
- Analyzes strength of the etched channels and inter-channel walls

- Medium Detail Focusing on Support Geometry
  - channel features roughly resolved
  - Higher mesh resolution in supporting walls
- For pressure loads and inter-channel thermal loads
- Analyses strength of supporting walls and structure

- Low geometry detail
  - Channels modeled as porous media
  - Highest detail in manifolding of PCHE
- For cross-heat exchanger thermal loads and manifold pressure loads.
- Analyzes strength of manifolds

# Examples of modeling for BPVC Certification

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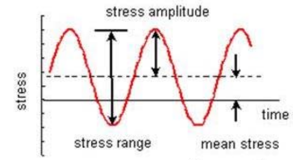
## VIII - Division 2 (non-nuclear)

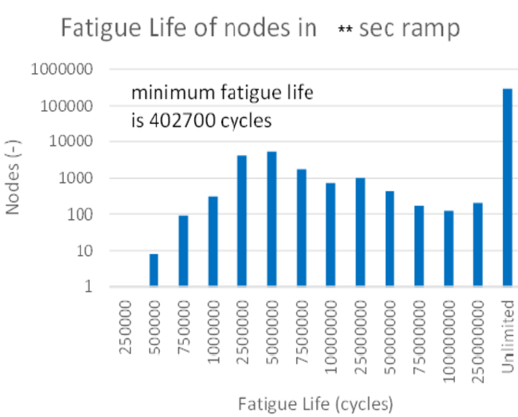
Fatigue life analysis of a PCHE chiller

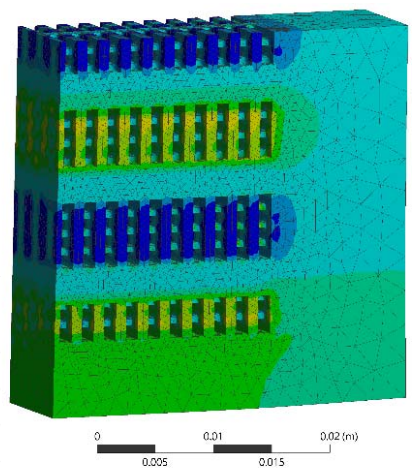
- stress cycles modeled at every node
- Node with larges stress amplitude limited life of the chiller




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

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

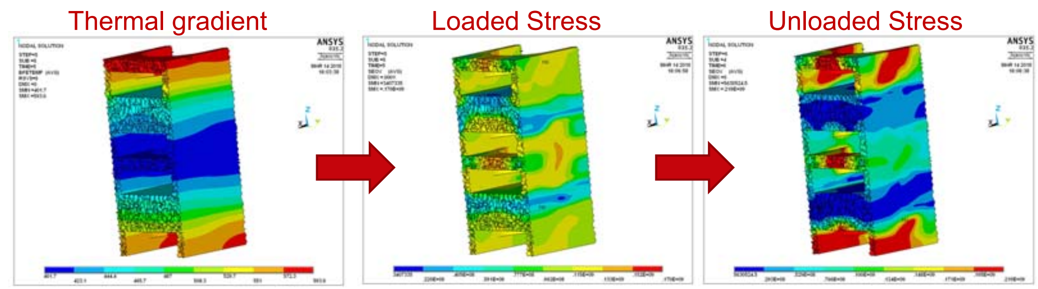


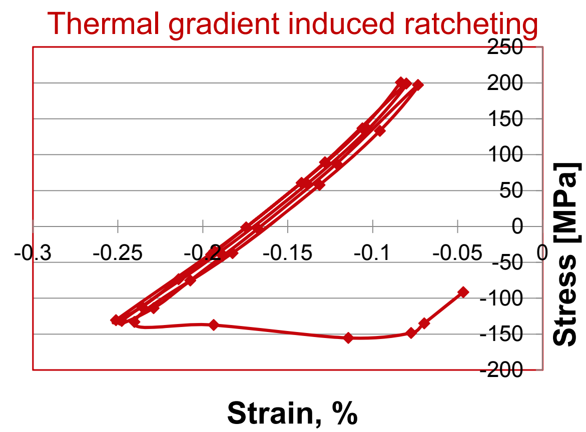




## III - Division 1 (nuclear service)

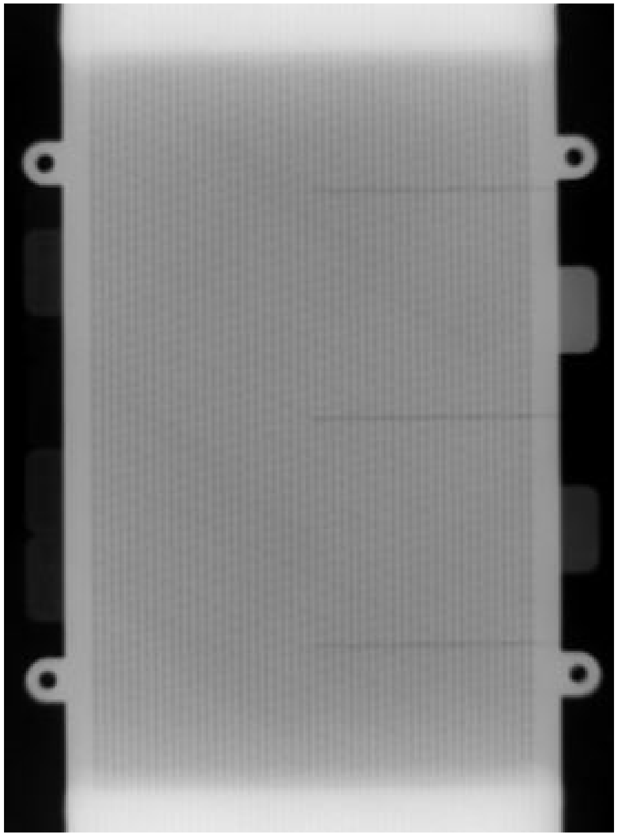
Thermally driven creep/ratcheting in core section of PCHE

- Large varying thermal gradients drive ratcheting of pressurized core section

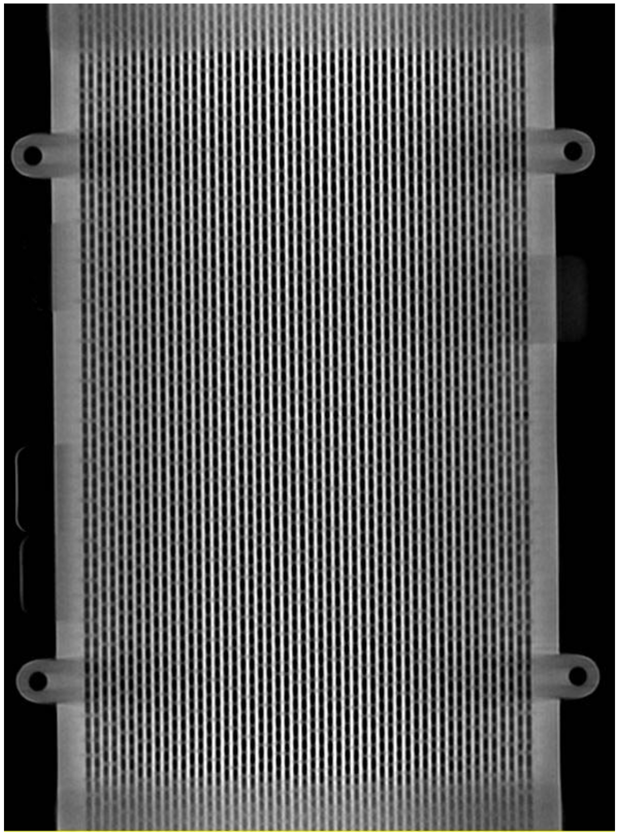


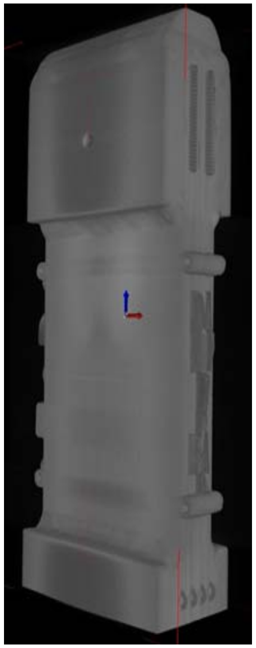
# Experimenting with NDE methods



Neutron Radiograph
~ 250 um resolution

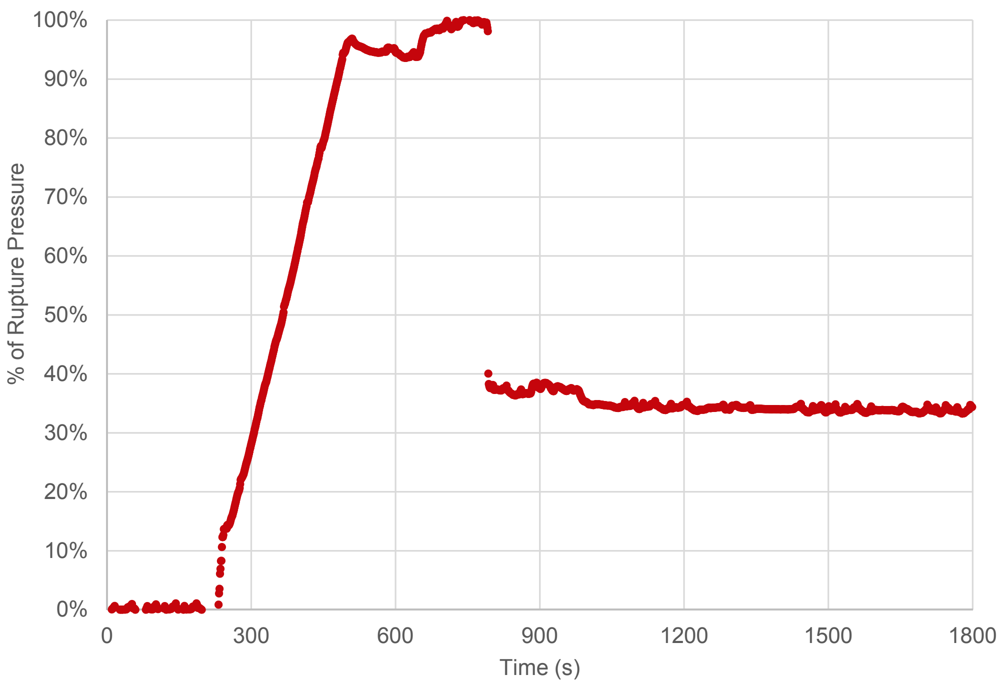


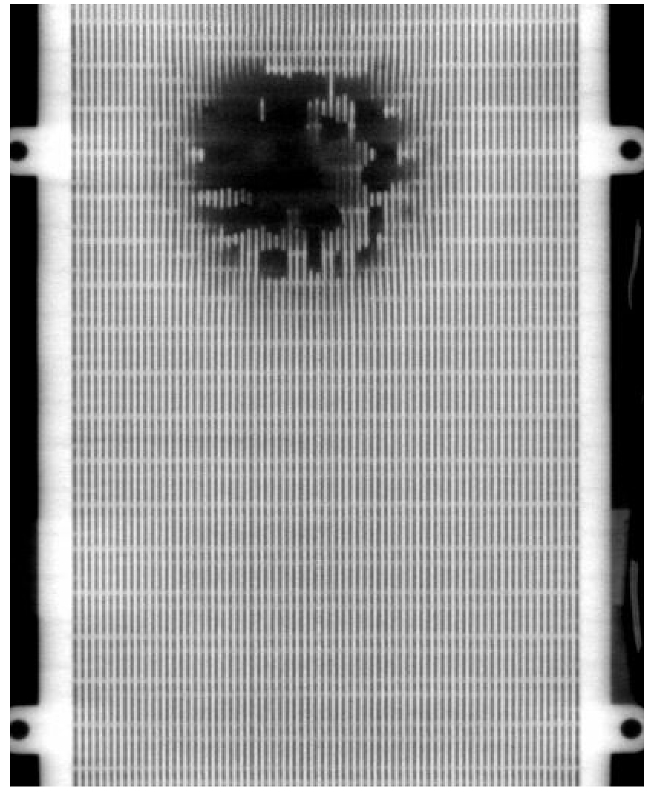
Slice from X-Ray Tomography
~ 150 um resolution

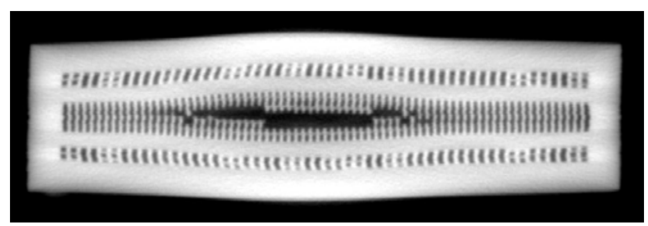


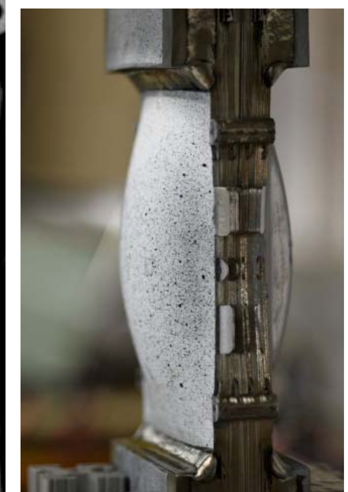
Additional Techniques: Ultrasound imaging & Eddy current testing by EPRI

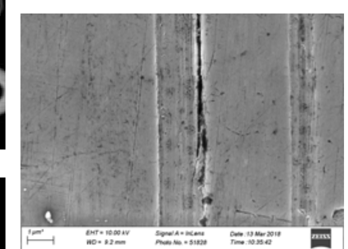
# Hydro "Burst" Testing









- UW constructed a 60,000psi hydrotesting facility to perform destructive testing on cores and headers.
- Delamination, or separation of shim, occurred in all four units tested at room temperature.
- DIC and strain gauges were used to record exterior deformation.
- X-ray tomography proved to be very useful for analyzing the core's interior before being cut for visual inspection.

## Summary

- Section VIII Code Case (non-nuclear) for PCHEs exists
- Gaps in PCHE Section III Code Case (nuclear) have been identified
- Test plan is being finalized to fill code and industry technical gaps
- Ongoing FEA analysis for creep and ratcheting units
- Creep and tensile strength tests of diffusion bonded 800H samples
- Lab-scale unit being ordered, testing will commence this fall
- X-ray system ordered by UW-Madison for preliminary inspection

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Thank you for your attention. Questions?