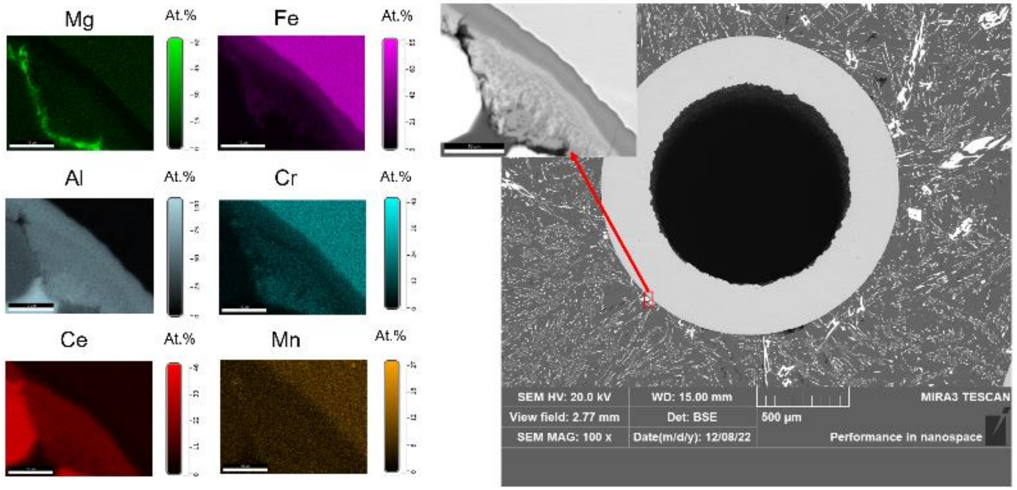
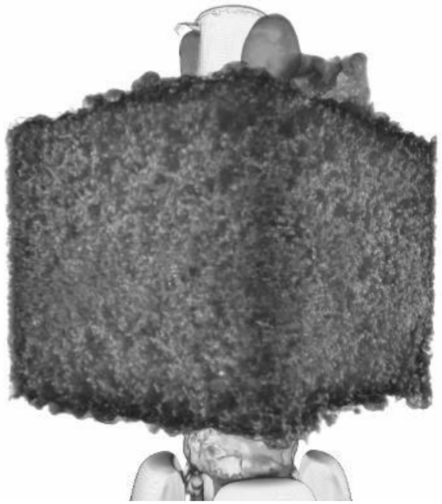
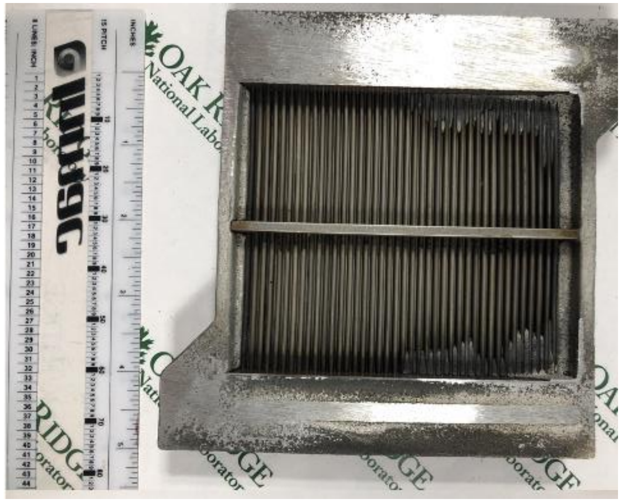
Al-Ce Alloy Based Compact Heat Exchanger (HX) for Refrigerant Charge Reduction and Unprecedented Durability







Oak Ridge National Laboratory
PI: Kashif Nawaz (Section Head), Presenter: Jamieson Brechtl
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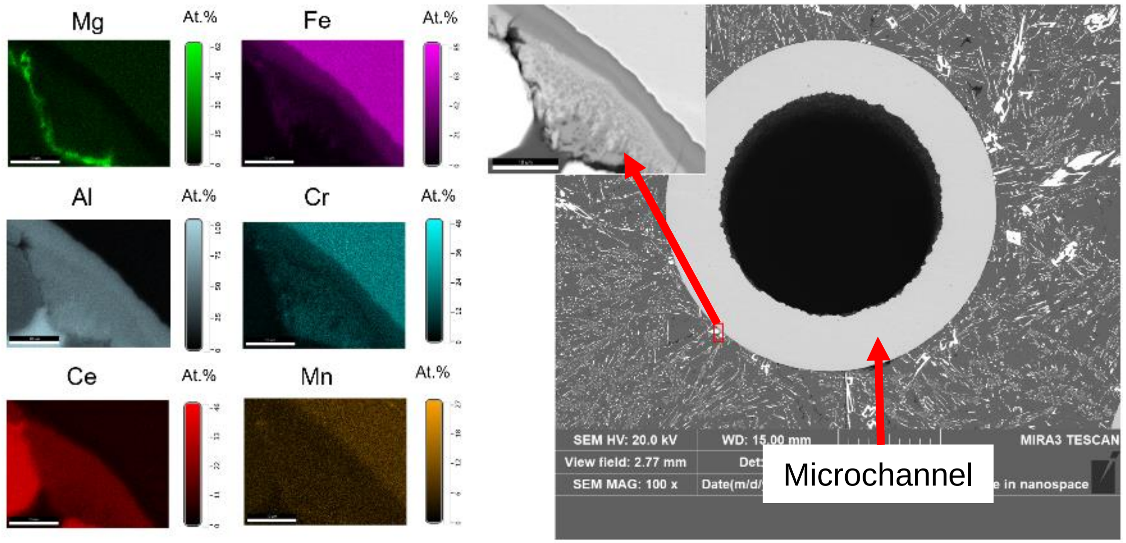
W.B.S: 3.2.4.99

Project Summary

Objective and outcome

The goal of the project jointly pursued by Oak Ridge National Laboratory (ORNL) and Eck Industries is to develop a scaled-up, die cast Al-Ce heat exchanger (HX) with excellent performance and 50% lower material cost than state-of-the-art condensing heat exchangers used in commercially-available furnaces and heating, ventilation, and air conditioning high-pressure condensers. The major objectives include the evaluation of the most critical properties relevant to the heat exchanger casting process and operation, which include castability, thermal conductivity, fluidity, corrosion resistance, and engineered mold design.



Team and Partners

ORNL: Kashif Nawaz, Michael Kesler, Jamieson Brechtl, Melanie Moses-DeBusk, Xiaohua Hu, Mingkan Zhang

Eck Industries Inc.: David Weiss

Stats

Performance Period: Jan. 2022 – Mar. 2024

DOE budget: $400k, Cost Share: $400k

Milestone 1: Characterize microstructure and thermal properties of Al-Ce HX (Jun. 30, 2022)-*Completed*

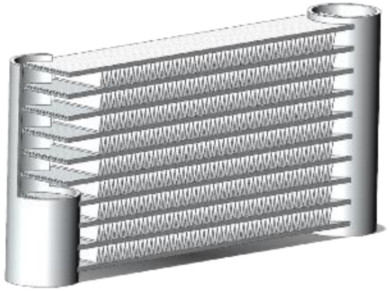
Milestone 2: Fabricate latest HX with designated improvements (Nov. 30, 2022)-*Completed*

Milestone 3: Complete the evaluation of the thermal performance and corrosion properties of prototype heat exchangers (Aug. 2023)-*In progress*

Challenges in Advanced Heat Exchanger Development

- Every home in America has an HVAC system.
- HVACs require HXs that are expensive to produce.
  - Manufacturing costs, assembly, complexity, and energy consumption are greatest problems.
- Heat exchangers account for more than 50% of energy consumption in a typical HVAC system.
- Corrosion: All US coastal regions experience severe corrosion rates impacting nearly 95M (1/3 US population) people.
  - HVAC condenser aluminum fins corrode within 5 years on FL coast.
- HX header joints are weakest points and brazing makes microchannel designs expensive.
- Refrigerant charge is a major technological challenge requiring advanced header development to reduce the required charge.
- High cost high-pressure HXs like CO_2.

Corrosion Susceptibility by Region



HXs fail in corrosive environments (i.e. in FL coastal regions HVAC condenser aluminum fins corrode within 5 years).

Solving these issues would provide improved functionality, reduced CO_2, and cost savings.

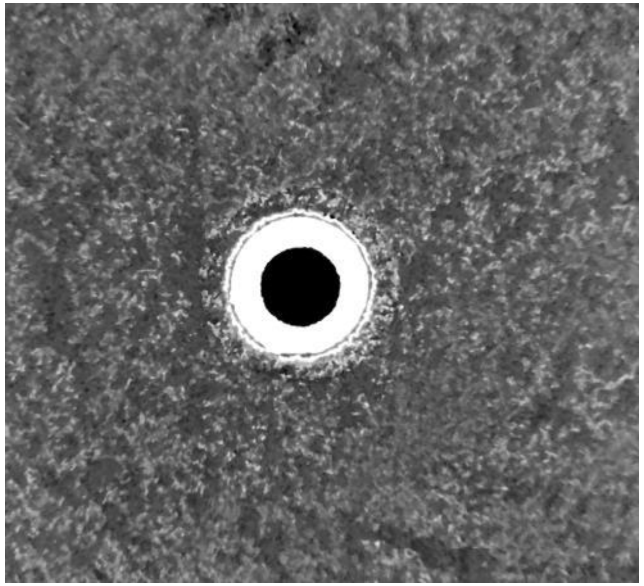
Problems with Current State-of-the-Art

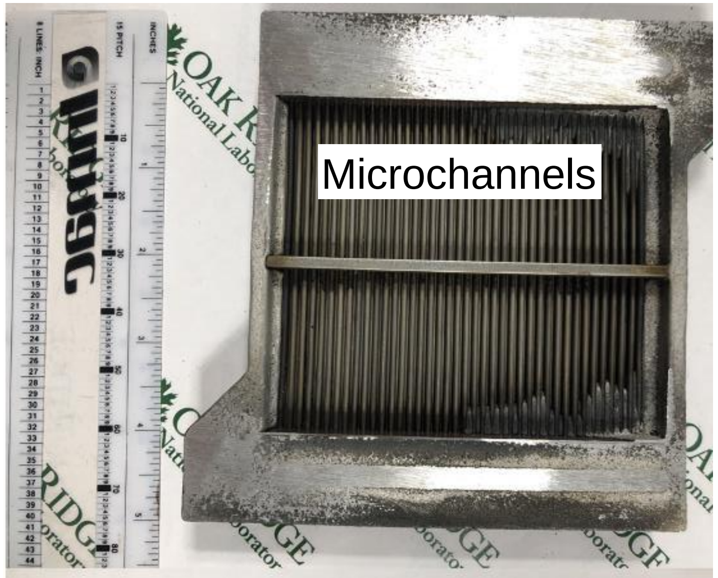
- Current state-of-the-art design:
  - Microchannels increase heat exchanger surface area while reducing refrigerant volume and still maintaining capacity.
- Problem: Complex, high temperature manufacturing process
  - Manufacturing conventional Al microchannel HXs (hydraulic diameter < 2 mm) multi-step process:
    - Tubes and headers manufactured separately via extrusion.
    - High temperature (600°C) brazing is required to combine tubes with headers at temperatures of in a dry atmosphere.
    - Manufacturing process slow, energy-intensive, and renders final part susceptible to leak.

Brazing process

Approach: Reduce Manufacturing Complexity

- Project approach:
  - Develop method to manufacture microchannel HX header in single piece from an Al-Ce alloy recently invented at ORNL.
  - Why is our design novel?
    - Stainless steel/Cu tubes reactively bonded into header during casting.
    - Corrosion resistant Al-Ce-Mg alloy.
  - Alloys enable use of a die cast mold to fabricate HX.
    - Lab scale development will employ low pressure sand molds.
    - Commercial stainless steel die cast molds can cost upwards of ~$100K.
    - Our fabrication method costs ~$2-5K.





Alignment and Impact

- *Improved resilience and reduced cost*

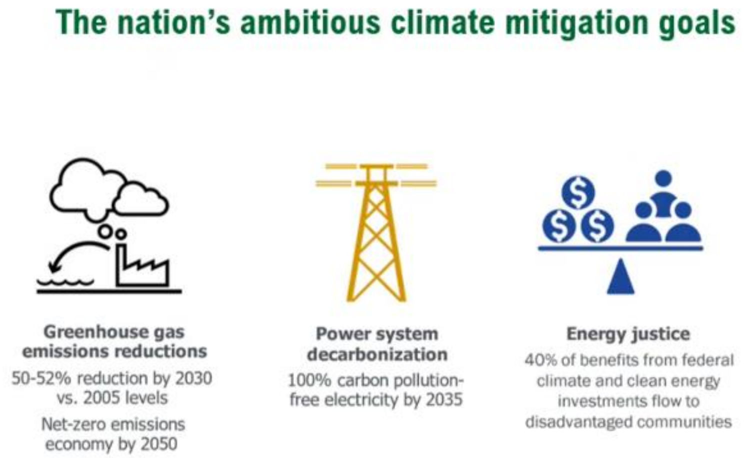
  Low-cost casting manufacturing process.
  - New potential geometries unlocked that otherwise cannot be cost effectively manufactured.

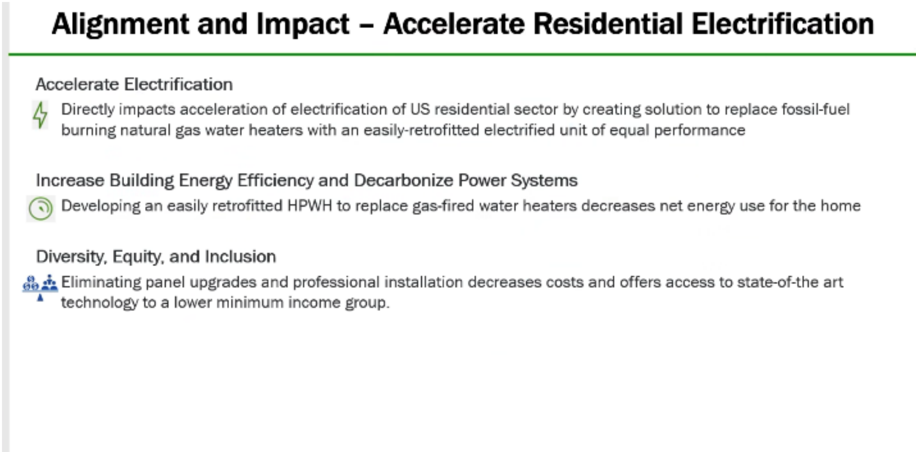
  Increased leak resistance.
  - Develop customized headers that can minimize refrigerant flow maldistribution.
  - Eliminates need for post-heat treatment.

- *Greenhouse gas emissions reduction*

  Substantial reduction in refrigerant charge and CO_2 emissions.

- *Better corrosion resistance and competitive mechanical strength*
  - Better corrosion resistance than conventional aluminum alloys.
  - Resistance to deleterious effects caused by corrosive exhaust gases.
  - High-pressure and temperature (~300 ^oC) applications.





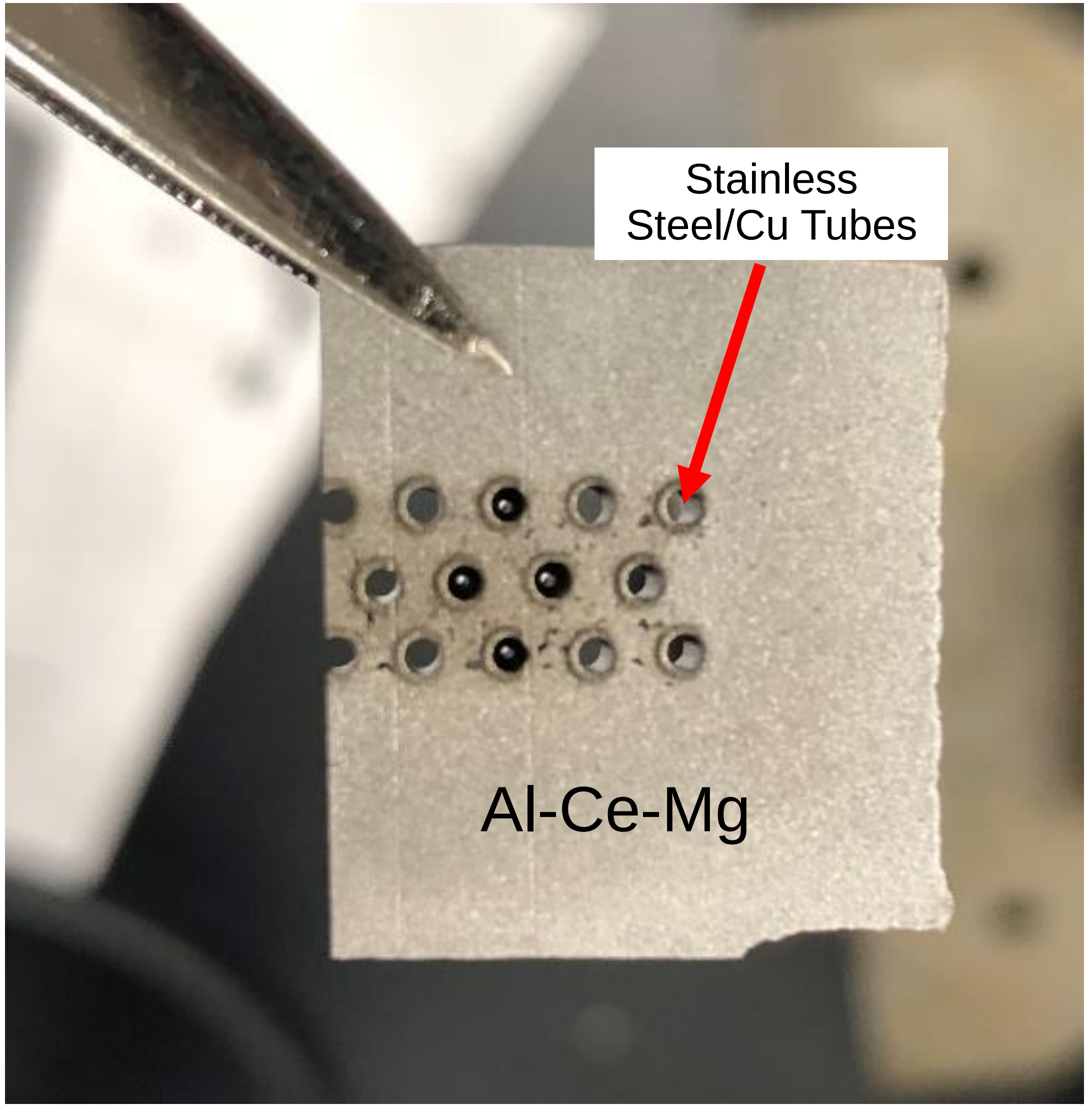
Project Progress: Material Candidates

- Alloys primarily consist of aluminum, cerium, and magnesium:

*Values in nominal weight percent.

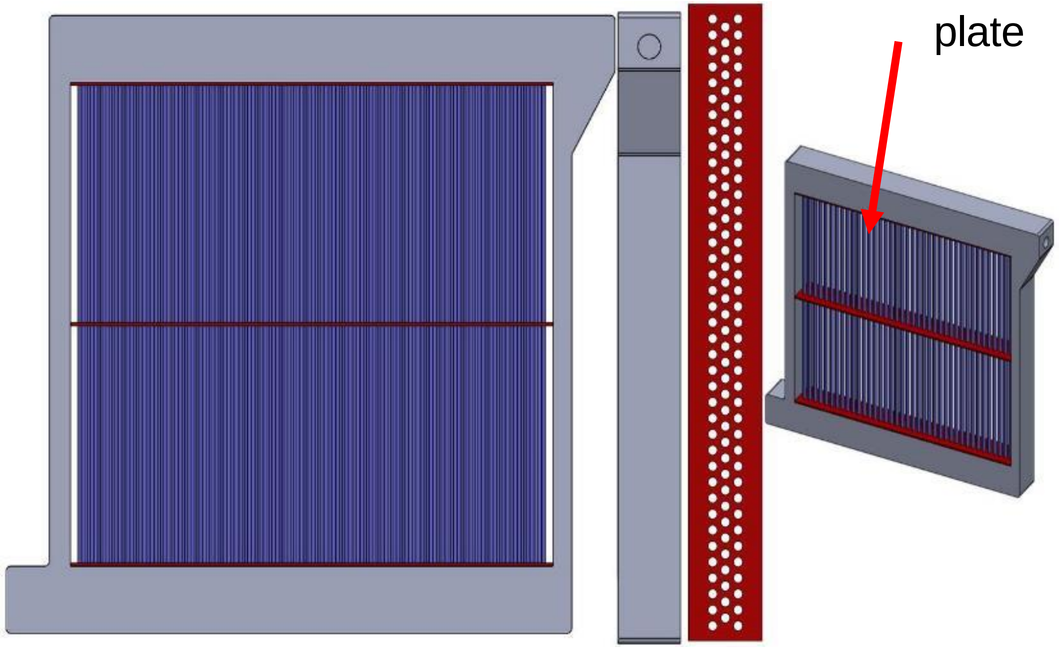
Sample	Aluminum	Cerium	Magnesium
Al-11Ce-0.4Mg	88.6%	11%	0.4%
Al-10Ce-5Mg	85%	10%	5%

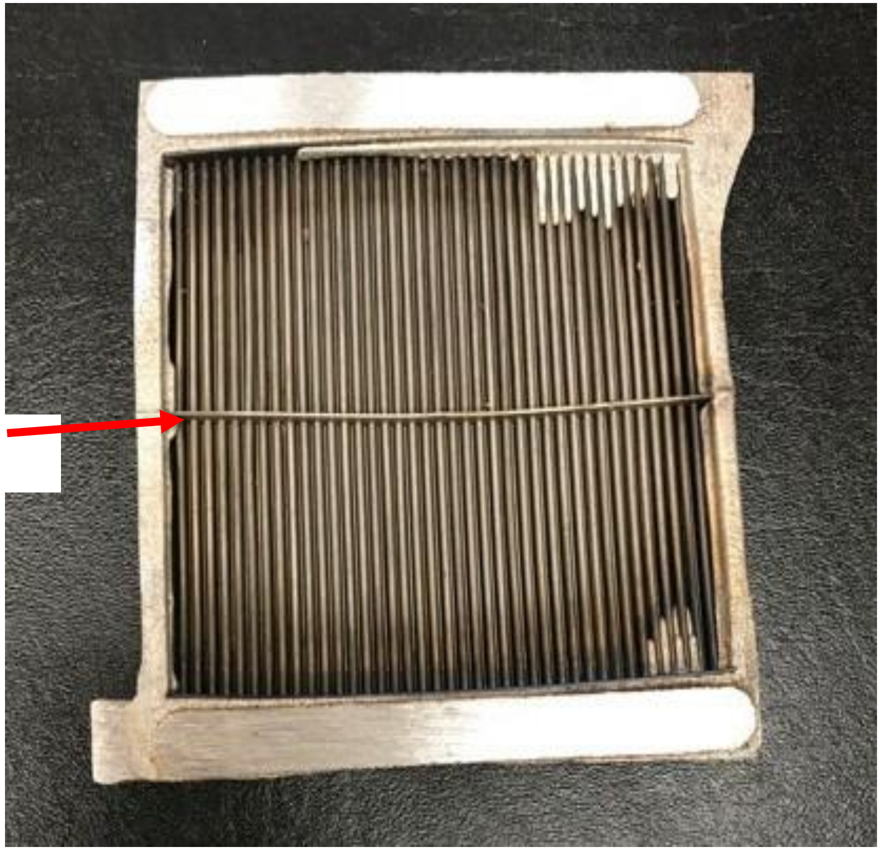
- These alloys were chosen due to their castability and corrosion resistance.
    - Al-10Ce-5Mg exhibited better castability.
- Melt pure elements in a furnace to fabricate material.
- Header material was fabricated using low pressure (5 – 15 psi) mold casting.



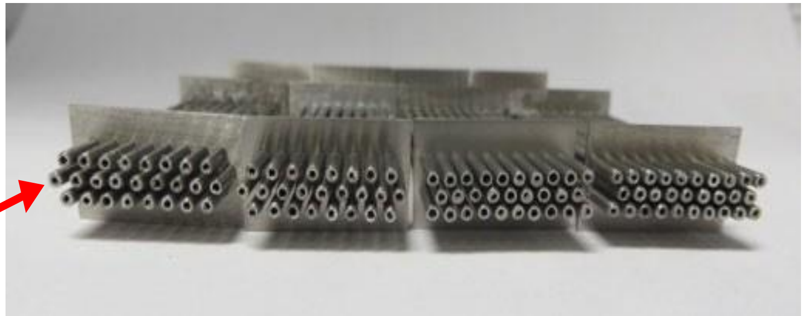
Project Progress: HX Design

Team *previously demonstrated* the ability to cast a full-scale heat exchanger with consistently spaced microchannels by the addition of a center stabilizing plate





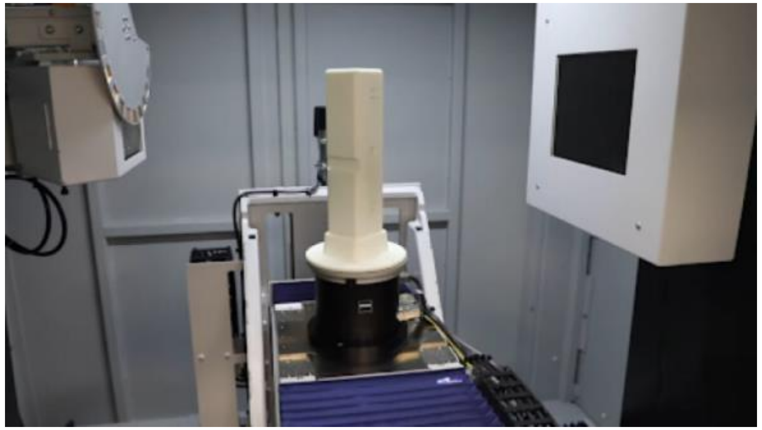
Center stabilizing plate

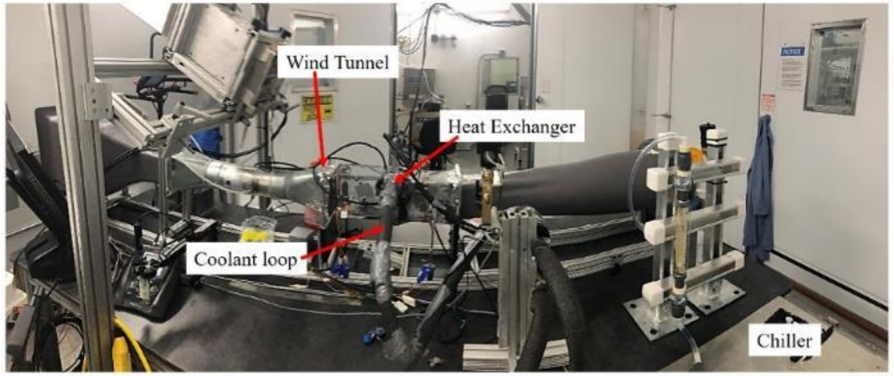


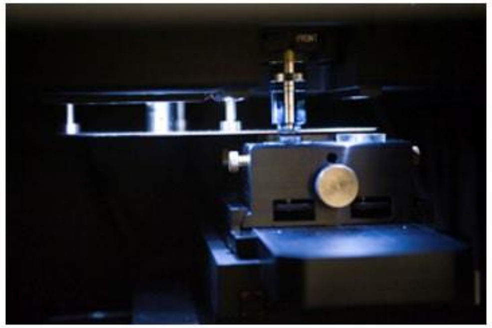
Stainless steel tube microchannel assemblies

Project Progress: Performance Characterization

- Completed work:
  - Mechanical testing: Vickers Hardness
  - Microstructural characterization methods at materials and component level:
    - X-ray computed tomography (XCT)
    - Scanning electron microscopy (SEM)
  - Heat transfer evaluation via wind tunnel experiments
- Ongoing work:
  - Corrosion testing with SEM and Vickers Hardness-*In progress*
  - Heat transfer evaluation via wind tunnel experiments-*In setup*

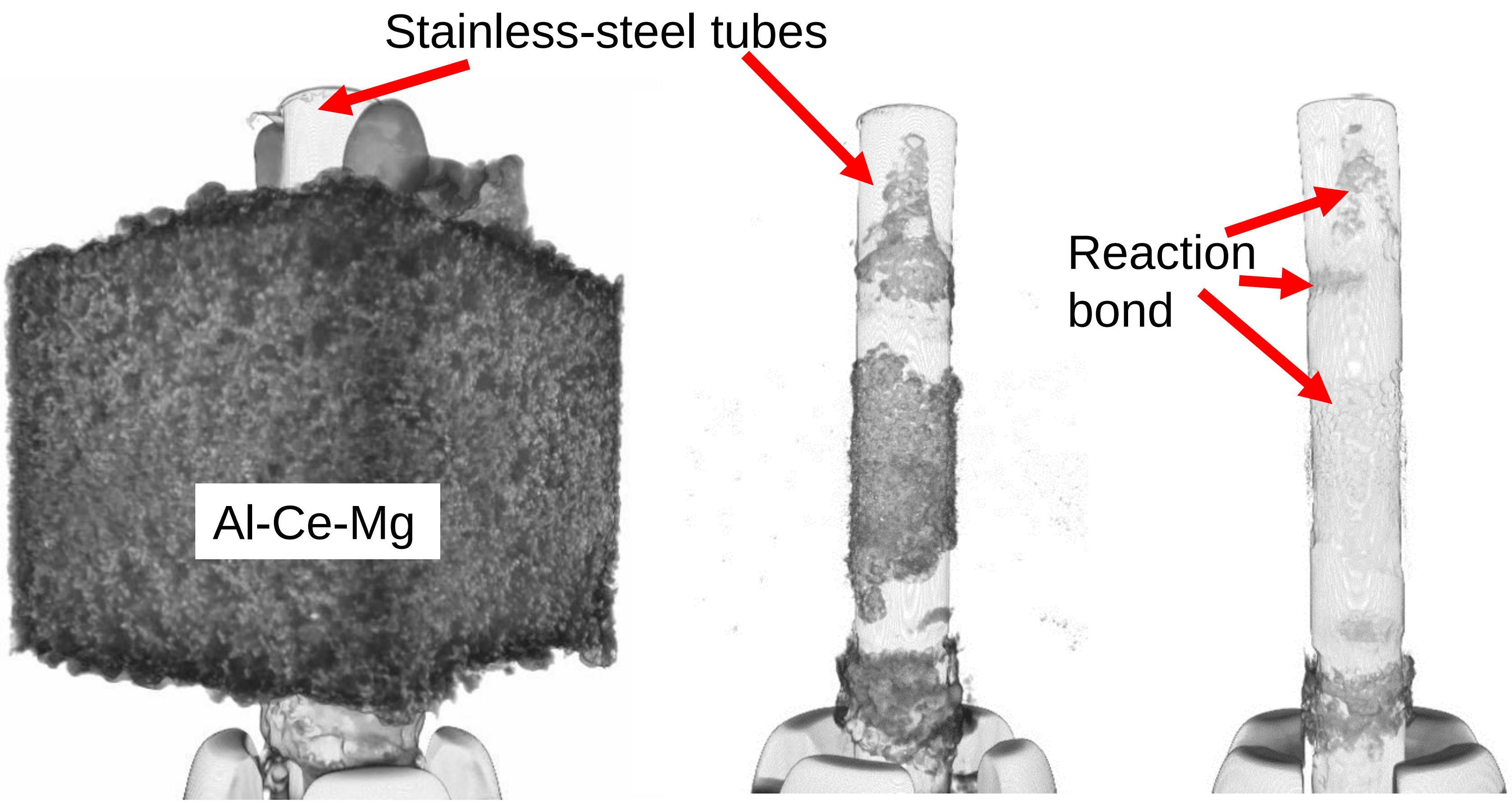






Project Progress: Successful Reaction Bond Formed

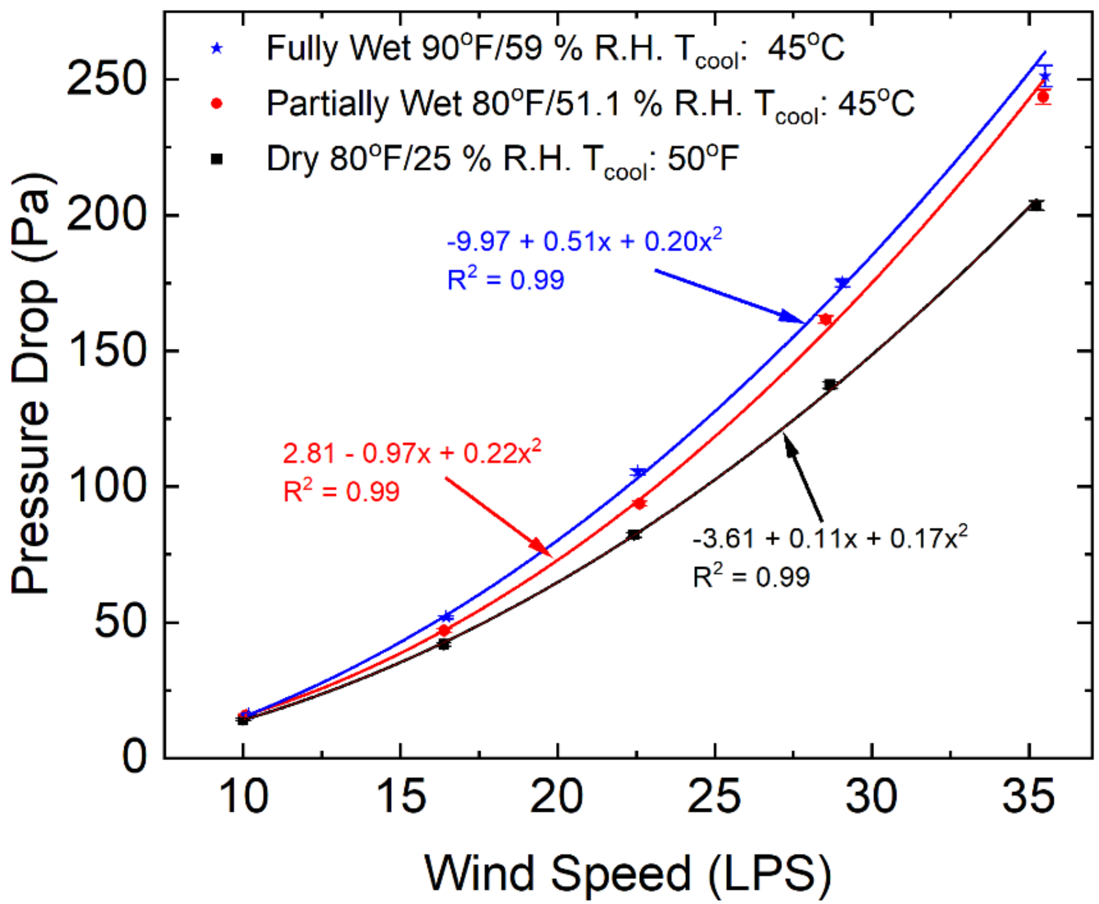
XCT results showed that bonding occurs between Al-Ce and steel/Cu.

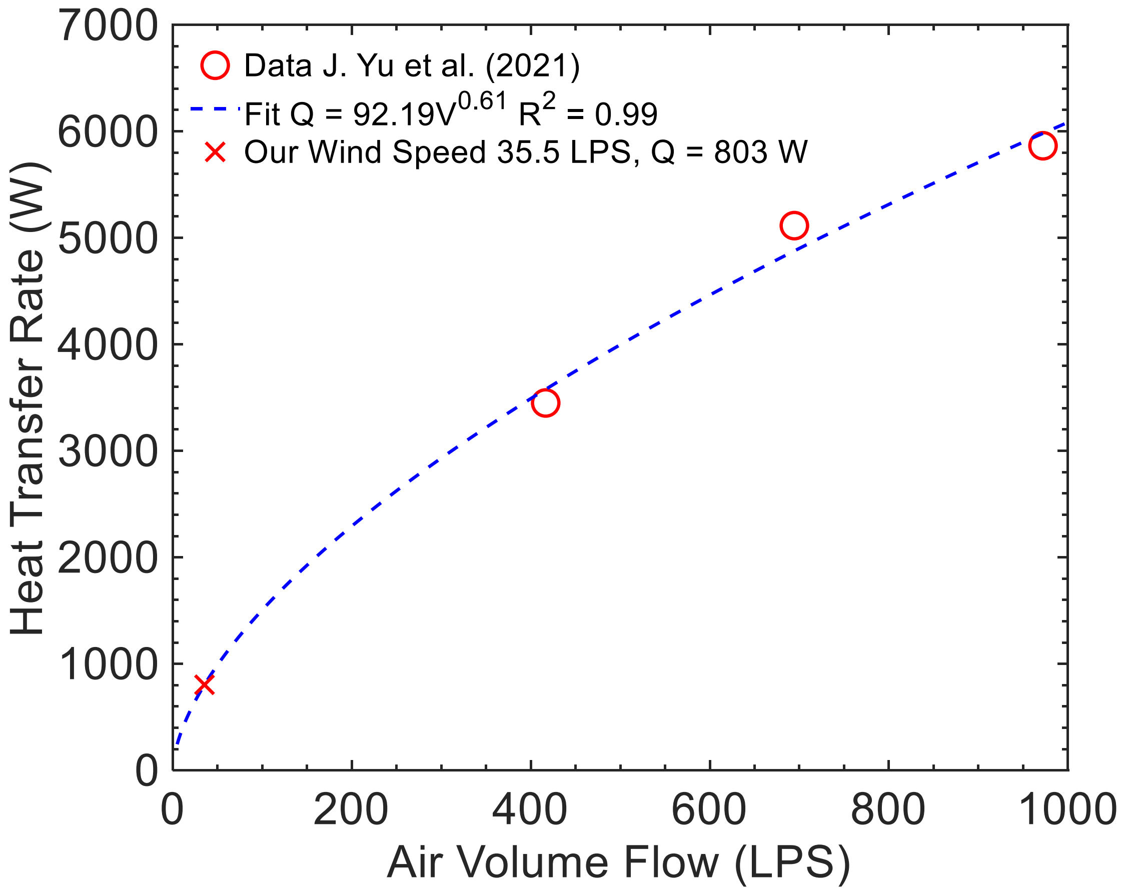


Both Steel and Cu are viable for casting Al-Ce-Mg over the tubes

Project Progress: Wind Tunnel Experiments to Assess Thermal Performance of Al-10Ce-5Mg HX

Results indicate that first cast HX exhibits thermal performance similar to that of other HXs. Expect improved performance during next casting trial.





J. Yu, et al., International Journal of Heat and Mass Transfer. 170 (2021) 121040.

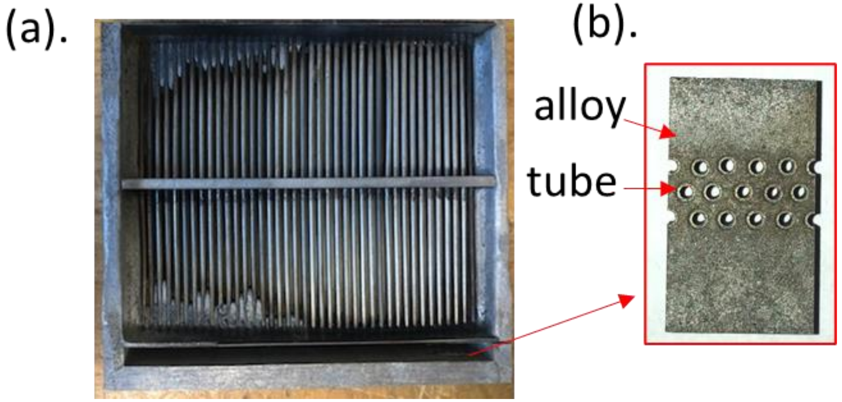
Project Progress: Issues

- Problems with current batch include:
  - Bent/clogged tubes (poor heat transfer).
  - Voids and porosity in Al-Ce alloy and poor Al-Ce/SS tube bonding (leaks).
  - Dual microstructure (structural properties issues).

- Solutions for next batch in progress:
  - Improved sand mold process to eliminate voids, porosity, and microstructure issues.
  - Modify header channel to eliminate bent/clogged tubes to improve fluidity and heat transfer performance.

Project Progress: Corrosion Experiments-*In Progress*

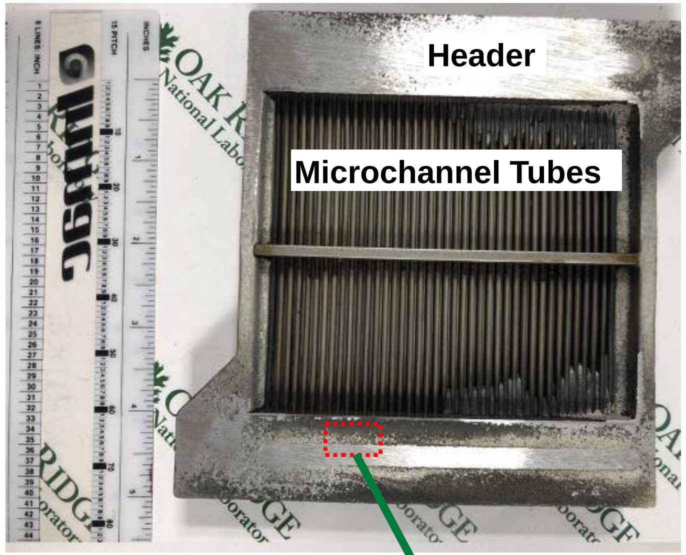
- Focus of task to better understand integrity of header-microchannel weld in extreme environments associated with HX applications.
- Investigate acidic durability and aging effect on morphology and chemistry of novel reactive bond interface between Al-10Ce-5Mg alloy and SS tubes.
  - HX header samples exposed to acid solutions at concentrations similar to standard condensing gas furnace (pH = ~3.5).
    - Cut small sections (0.75” long) to expose the alloy-SS weld area
    - 14 ppm formic acid, 2 ppm nitric acid, and 2 ppm sulfuric acid for 250 hrs
- Characterize samples before and after testing using following techniques:
  - Scanning electron microscopy (SEM)
  - Energy dispersive X-ray spectroscopy (EDS)
  - Vickers hardness testing

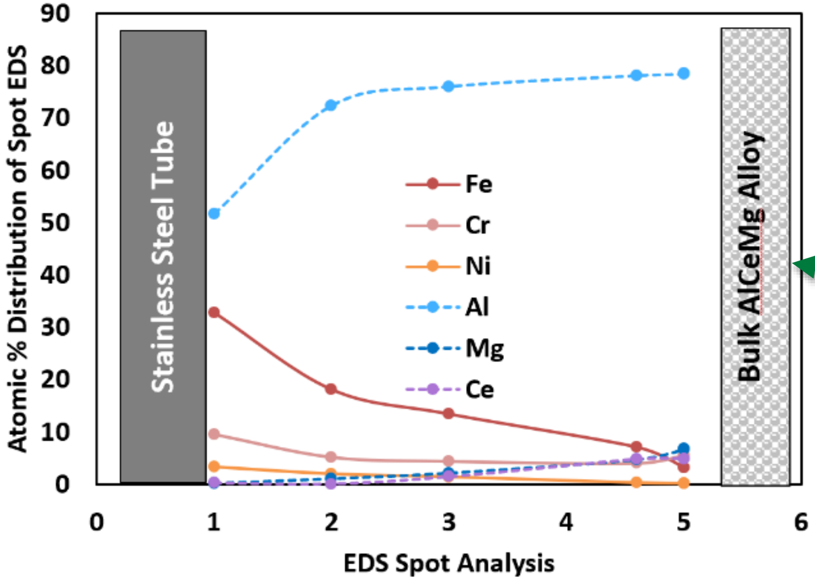


(a) HX with Al-10Ce-5Mg headers connected by SS tubes. (b) Sample cut from HX header by EDM. Arrows indicate area of HX in (a) from which the sample was taken. The alloy and SS tube areas of (b) are indicated by the red arrows.

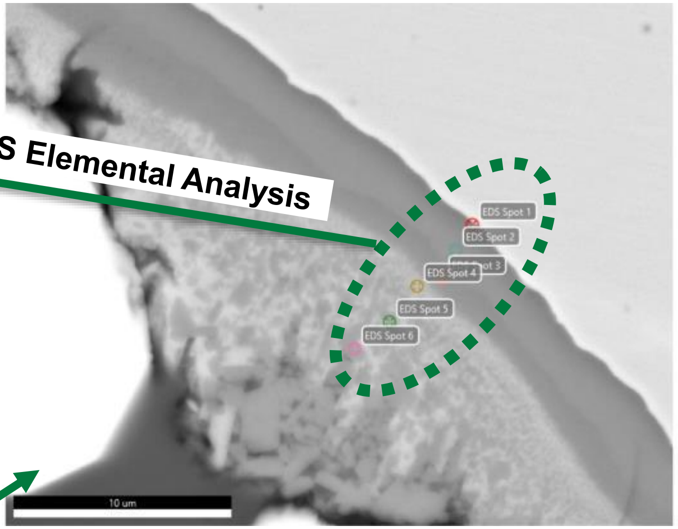
Results will help shed light on usefulness of microchannel Al-Ce-Mg HX in standard condensing gas furnaces

Project Progress: Preliminary SEM-EDS Characterization

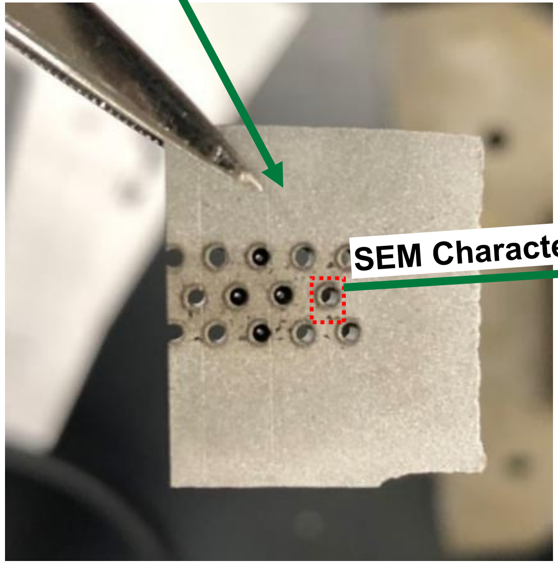




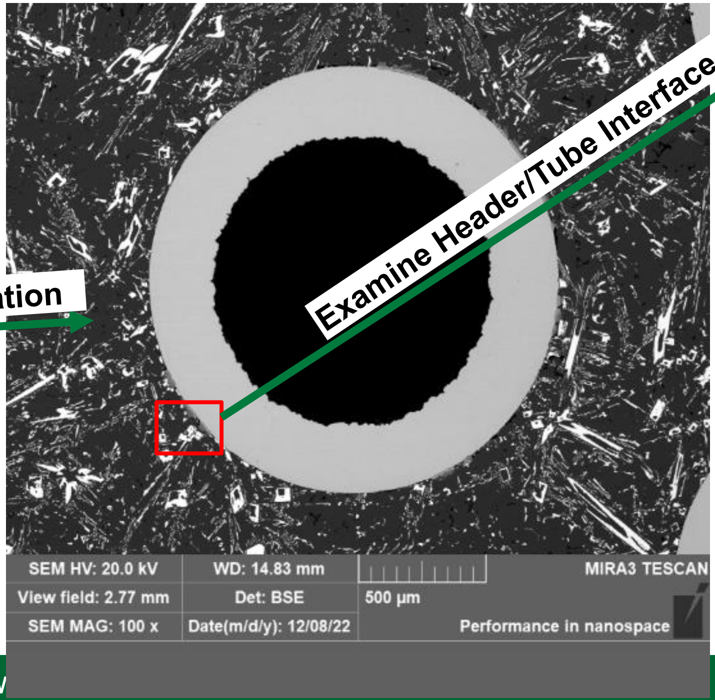
EDS Elemental Analysis



Cut sample out



SEM Characterization

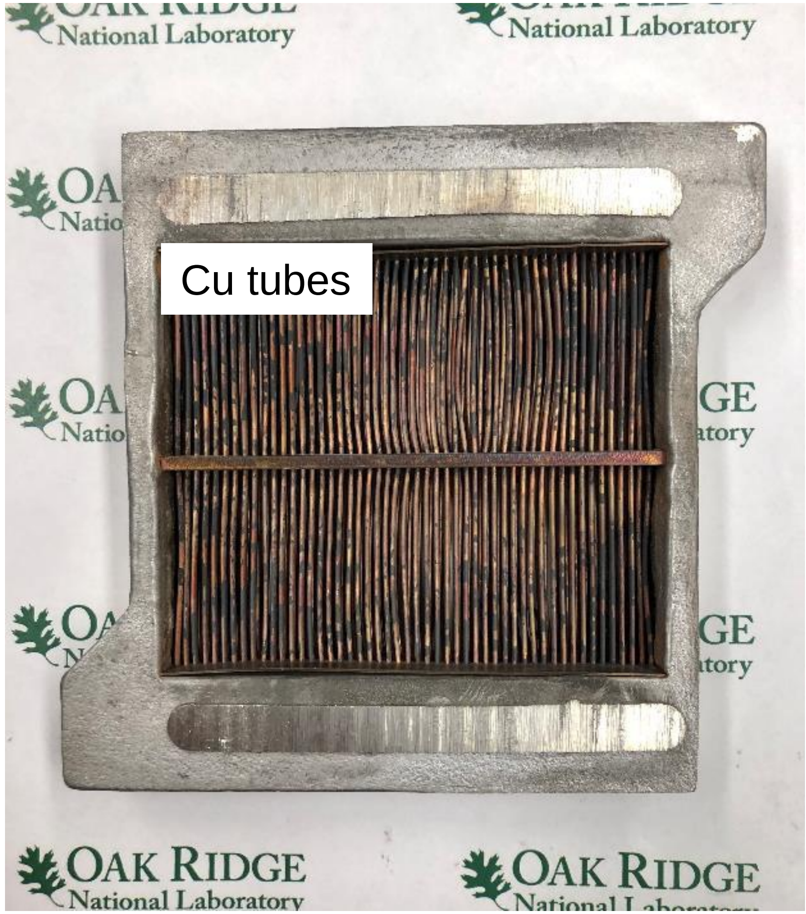


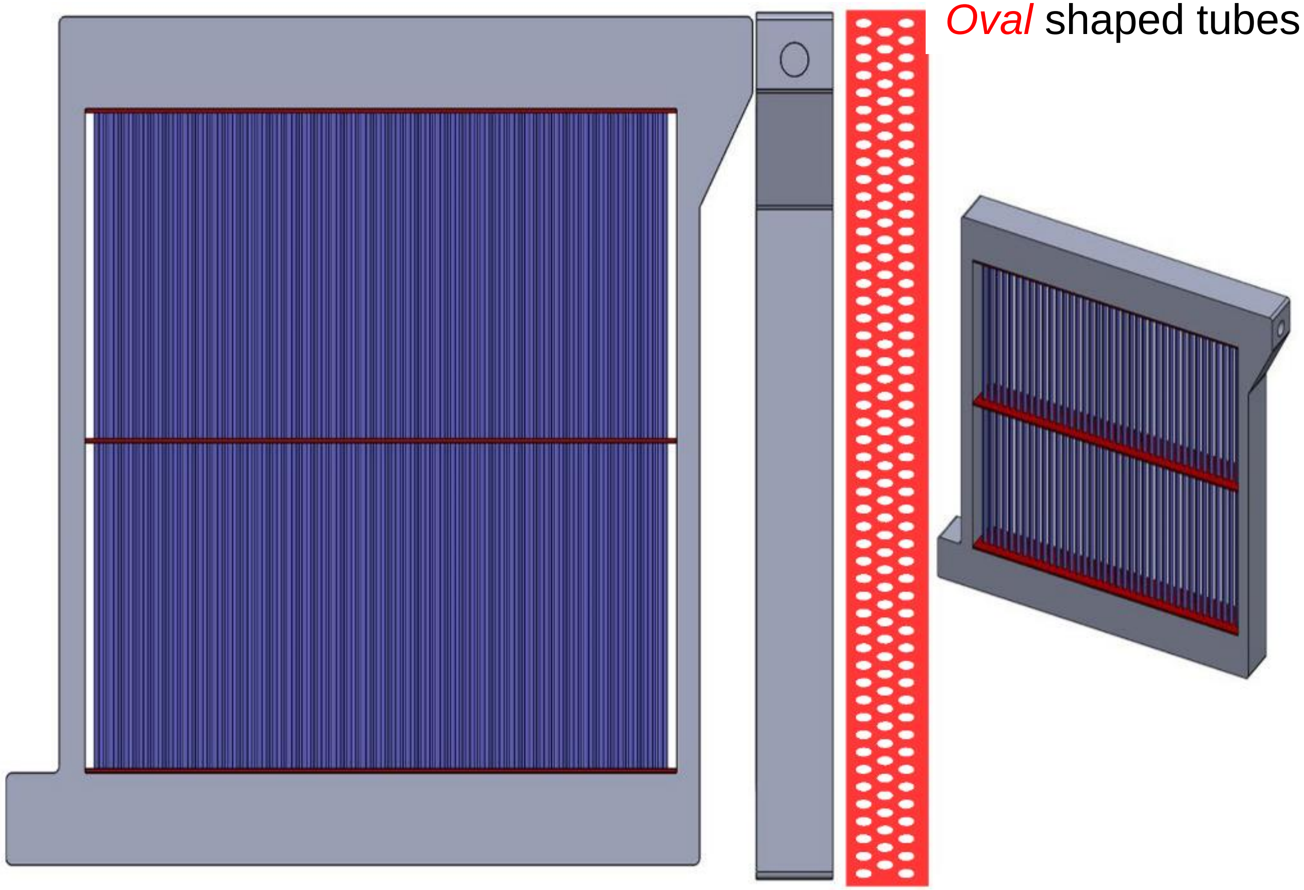
Examine Header/Tube Interface

Successively formed reactive bond between header and stainless-steel tubes

Project Progress: Improved Al-10Ce-5Mg HX samples

- Replaced stainless steel tubes with Cu ones
- Replaced circular tubes with ***oval*** shaped tubes to enhance thermal performance





Dissemination

- Milestone reports-*In Progress*:
  - Corrosion and Thermal Performance of a Die Cast Al-Ce Heat Exchanger
- Multiple publications (fundamental and applications)-*In Progress*:
  - Corrosion Resistance of Fe-Al Reactive Bond Weld from casted AlCeMg alloy
  - Prototyping of a Casted Aluminum Cerium Micro Heat Exchanger
- Presentations-*In Progress*:
  - Thermal Properties and Corrosion Response of cast Al-Ce-Mg alloy for Heat Exchanger Applications

Industry Engagement:

Eck Industries, Inc.
Specialists in premium aluminum castings

Summary and Future Work

Summary	Future Work

Summary

- Successfully performed planned heat transfer and microstructural characterization of HX
  - Issues encountered so far include HX material problems such as voids, leakage, and clogged tubes
- Improving casting process to mitigate these issues

Future Work

- Perform corrosion testing
- Test newly casted HX in the wind tunnel to examine thermal properties
- Share findings with research community

Thank you

Oak Ridge National Laboratory

PI: Kashif Nawaz (Section Head),

Presenter: Jamieson Brechtl

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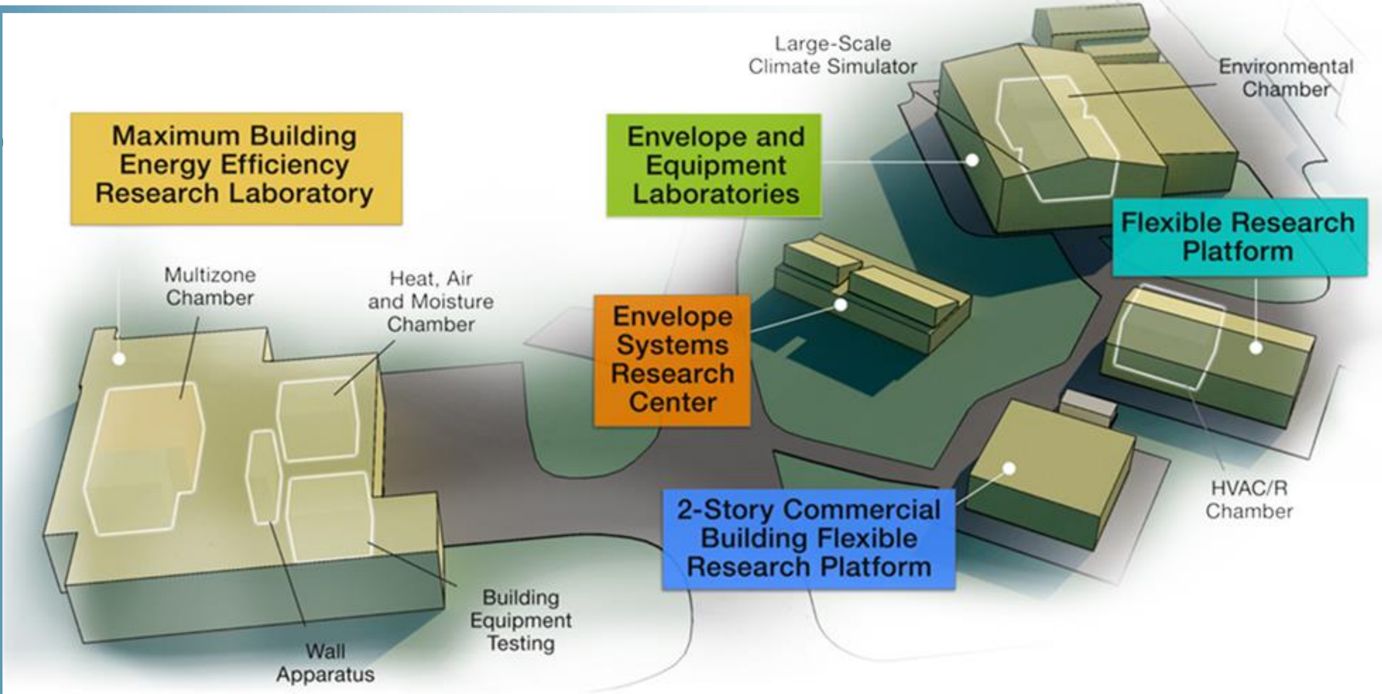

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Scientific and Economic Results

236 publications in FY22
125 industry partners
54 university partners
13 R&D 100 awards
52 active CRADAs

BTRIC is a DOE-Designated National User Facility

REFERENCE SLIDES

Project Execution

			Year 1				Year 2			
Task	Subtask		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
1		Characterization and comparison of microstructural stability and mechanical behavior			◆					
	1.1	Perform X-ray computed tomography								
	1.2	Perform Vickers hardness tests								
2		Heat exchanger performance testing		◆						
	2.1	Test heat exchanger in wind tunnel								
3		Corrosion testing of heat exchanger								
	3.1	Perform preliminary scanning electron microscopy								
	3.2	Perform immersion corrosion experiments								
	3.3	Perform exsitu scanning electron microscopy								
4	4.1	Modified heat exchanger performance testing								
	4.2	Test modified heat exchanger in wind tunnel								
5		Finalize publications and submit to journal								

◆ Completed

Team

- **Oak Ridge National Laboratory:**
  - Kashif Nawaz (Section Head/Group Leader)
  - Michael Kesler (R&D staff)
  - Jamieson Brechtl (R&D staff)
  - Melanie Moses-DeBusk (Senior R&D staff)
  - Xiaohua Hu (R&D staff)
  - Mingkan Zhang (R&D staff)

- **Eck Industries Inc.:**
  - David Weiss (VP R&D)