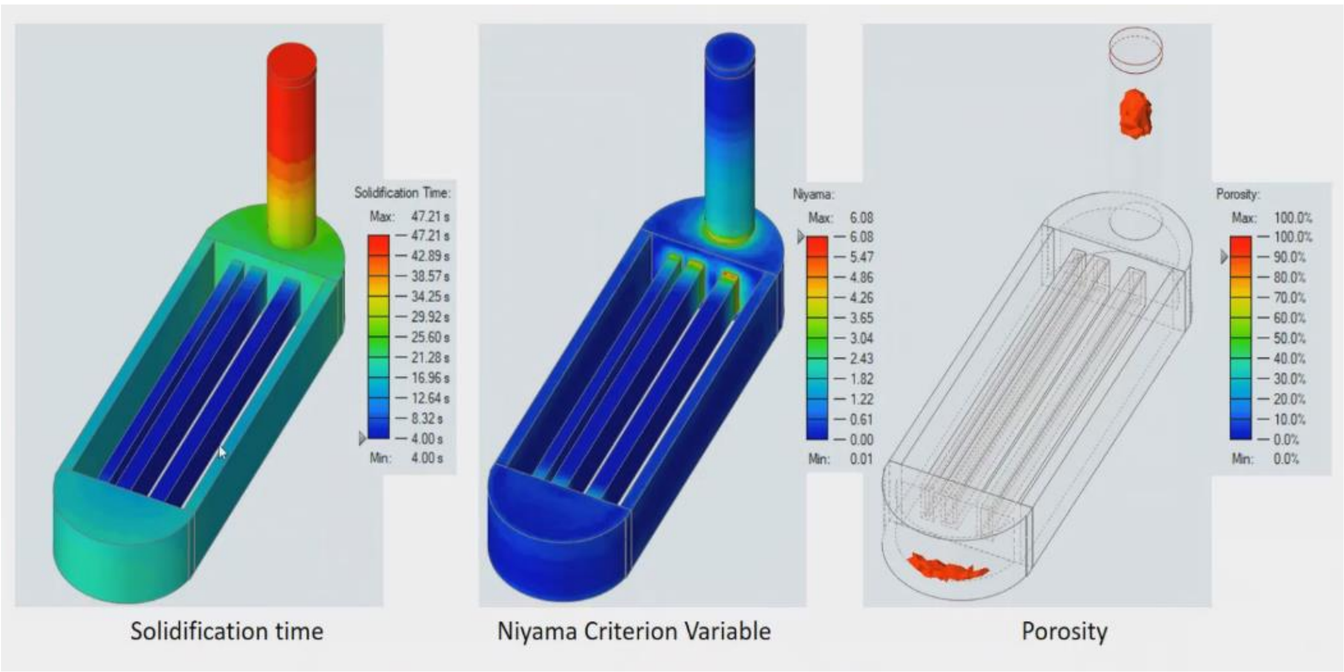
U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

The Novel Cast Aluminum-Cerium Heat Exchanger



Oak Ridge National Lab/ECK/Virginia Tech./UMD

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Project Summary

Timeline:

Start date: Oct 1, 2018

Planned end date: Sept 30, 2021

Key Milestones

1. Identify aluminum-cerium (Al-Ce) casting limitations (Sept 30, 2019)
2. Fabricate and evaluate 1 kW cast heat exchanger (HX) (Sept 30, 2020)

Budget:

Total Project $ to Date:

- DOE: $443K
- Cost share: $10K

Total Project $:

- DOE: $1,327K
- Cost share: $50K

Key Partners:

Eck Industries, Inc.
Specialists in premium aluminum castings

University of Maryland 1856

Virginia Tech

Project Outcome:

- Development of the first microchannel HX that is die-cast in one piece, including the headers, eliminating the need for brazing or welding
- Successfully development of a method of manufacturing low-cost high-pressure microchannel HXs that will increase the viability of several technologies and contribute to meeting DOE's energy intensity targets specified in the Multi-Year Program Plan
- Energy saving potential: 1.15 Quad

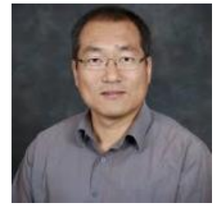
Team

HX, HVAC, and System Integration, Expertise









Al-Ce Alloy Inventors, Material Expertise


OAK RIDGE National Laboratory

HX Design Expertise



UNIVERSITY OF MARYLAND 1856

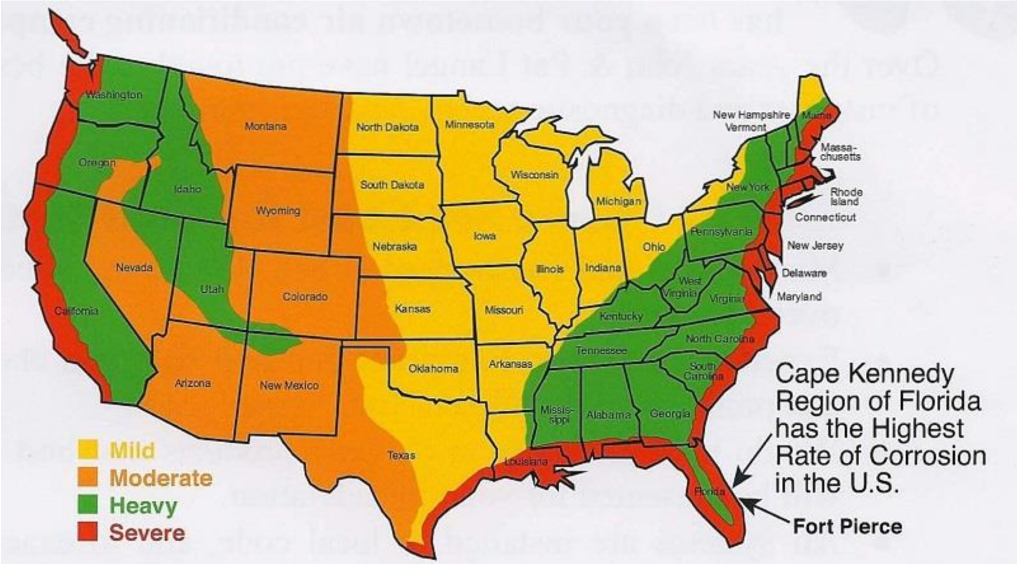
Multiphysics Modeling


VIRGINIA TECH

Challenge

Problem Definition:

- HXs leak (joints are the weakest points)
- Mircrochannel HXs are expensive (manufacturing processes are expensive)
- High-pressure HXs are expensive (CO_2 HXs are very expensive)



Corrosion map of the U.S.

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

- Condensing furnaces' secondary HX is made of expensive SS alloys

Advice:

- Innovative manufacturing technologies and advanced alloys are needed to address these issues

Brief Background

- Aluminum was more expensive than gold in 19th century.
- In 1850, aluminum was $37,200/kg, but gold was $20,500/kg
- In 1884 when the Washington Monument was finalized, a 2.8 kg aluminum pyramidon was placed at the top
- In 1889, the Bayer, Hall process was developed, which significantly reduced the cost of aluminum extraction
- Today, aluminum is being used in HVAC, automotive, aviation, power generation, and other industries

Take-Away Message:
A new material/alloy/manufacturing processes could potentially revolutionize many industries!

Approach

Critical Materials Institute
AN ENERGY INNOVATION HUB

In 2015, ORNL invented the Al-Ce alloy under Critical Material Institute Funding!

Al-Ce Advantages

- **Castability**
  - Unlocks new potential geometries that otherwise cannot be cost effectively manufactured
  - Leak resistance
  - Customized headers that can minimize refrigerant flow maldistribution
- **Corrosion resistance**
  - Better corrosion resistance than conventional aluminum alloys
  - Reduced degradation of Al fins in **coastal** areas.
  - Indoor coils—avoids formicary corrosion that can cause refrigerant leaks in copper tubes
  - Corrosive exhaust gases
- **Mechanical strength (including at high-temperatures)**
  - High-pressure applications
  - High-temperature applications
- **Lower manufacturing cost**
  - Low-cost casting manufacturing process
  - Eliminates the need for post-heat treatment

Approach

Sand/DIE cast the whole HX in one piece to

- Eliminate the joints (source of the GWP refrigerant leaks)
- Reduce the manufacturing cost of HXs by 50% (by eliminating the expensive posttreatment and increasing throughput and automation)
- Increase the operating pressure of HXs by adding internal structures that cannot be achieved with conventional manufacturing processes (very important for CO_2 systems or HP water heaters)
- Increase the corrosion resistance

Approaches to Market

Manufacturing Al-Ce fin stock and extruded tubes	Casting headers to tubes	Casting complete part

→ Increasing manufacturing challenge

→ Increasing benefit from Al-Ce

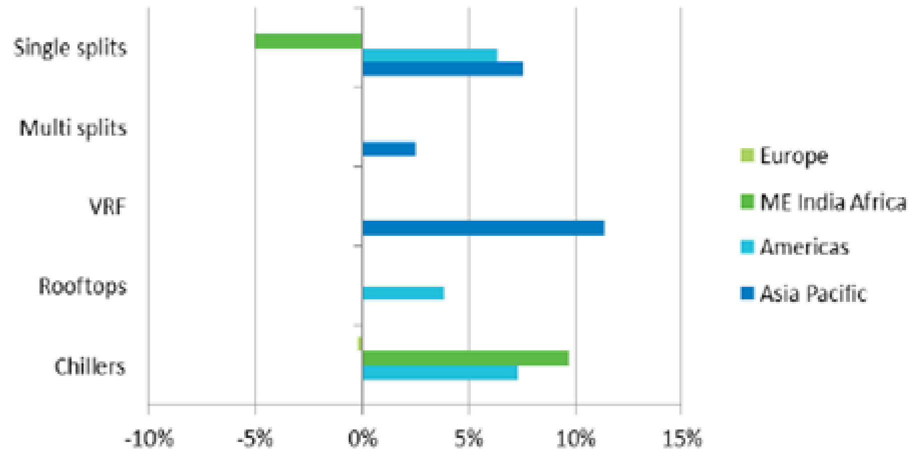
Retain today's manufacturing techniques: gain strength and corrosion resistance	Viable manufacturing process: gain leak resistance and improved flow distribution and higher-volume, next-generation HX production	Advanced casting: greatest benefit from material and process

Al-Ce Markets and Various Applications

- **Castability**
  - Novel geometries: advanced high-performance HXs including ***aerospace, auto***
  - Leak resistance: all applications, especially ***flammable/toxic refrigerants, refrigeration***—high charge levels
  - Customized headers—evaporator applications (***building or mobile AC***)
  - Cost—major driver in ***all applications***. Avoids volatility in copper price
- **Corrosion resistance**
  - *Residential/commercial AC*
  - *Gas furnaces, secondary HX/waste heat recovery*
- **Mechanical strength (including high temperature)**
  - *CO_2 HPWHs, refrigeration*
  - *Furnaces, waste heat recovery*

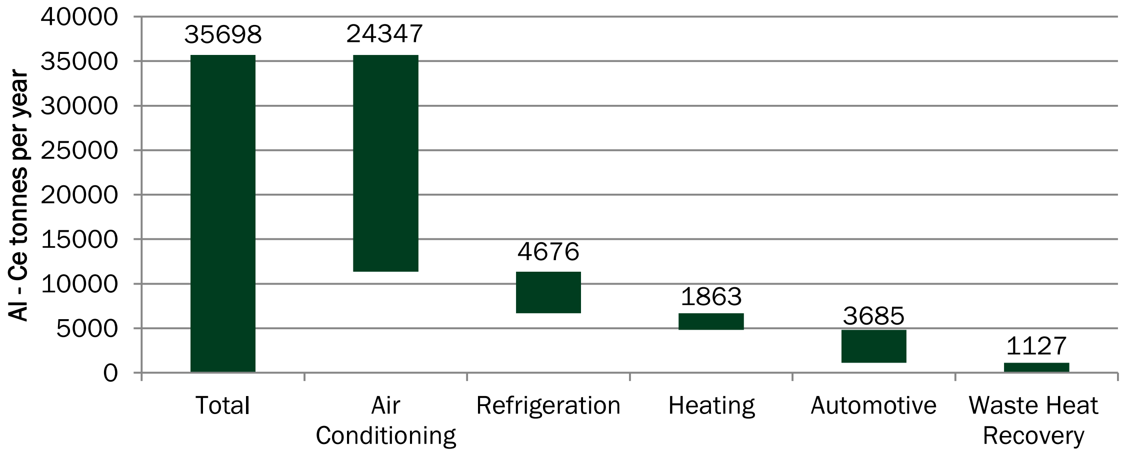
Impact: Al-Ce HX Market Potential

- HVAC
- HPWH
- Furnaces
- Refrigeration
- Waste heat recovery
- Automotive



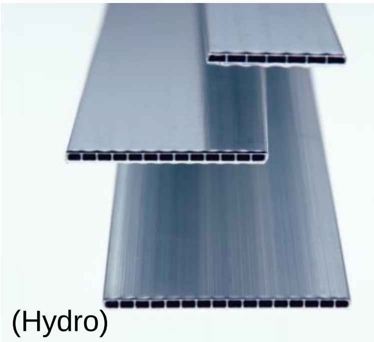
Source: BSRIA, Interrelation/ future trends in use of copper for air conditioning, May 2018

2025 forecast rate of *copper displacement to Al* in HVAC markets (2025).



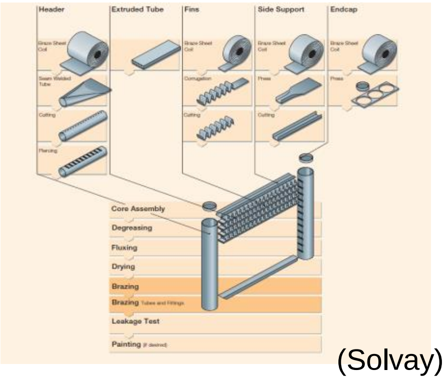
Estimated viable US market sizes.

Aluminum Microchannel Manufacturing


(Hydro)

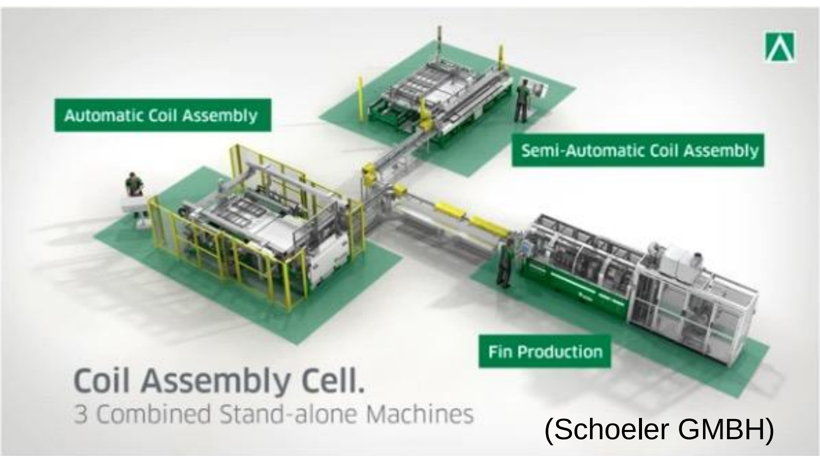
Extruded microchannels
Small feature sizes:
0.1 mm fins,
<1 mm channels


(Sanhua)

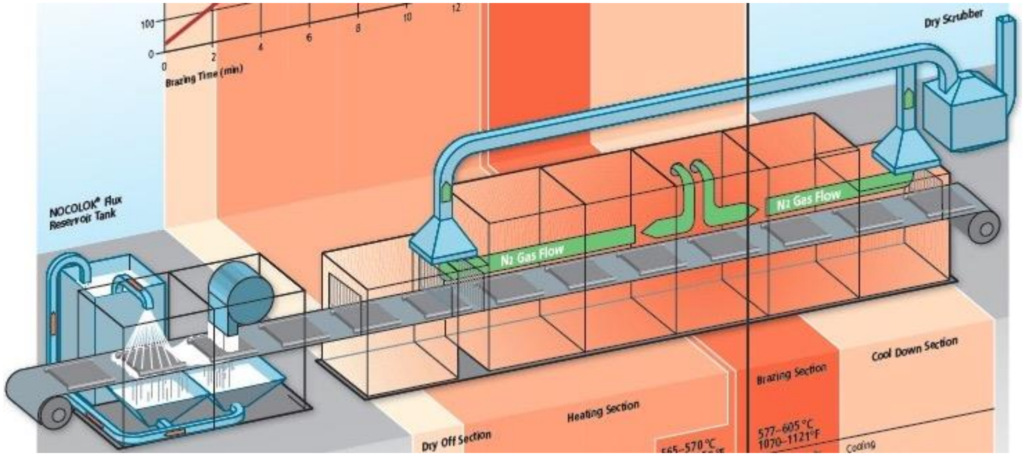


(Solvay)

- **Fin stamping, assembly, fluxing, drying, brazing in controlled atmosphere brazing (CAB) furnace**



(Schoeler GMBH)



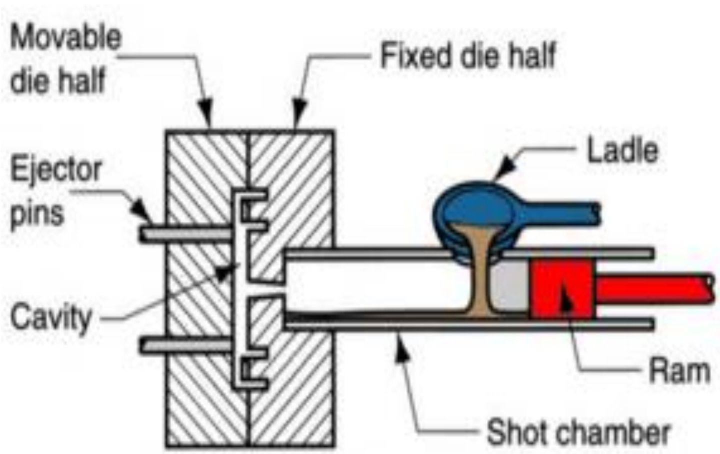
(Solvay)

- **Throughput: 500,000 units/year**
- **Manufactured cost: ~$2–$4/lb (excludes the capital cost/markup)**

Casting Processes with Al-Ce

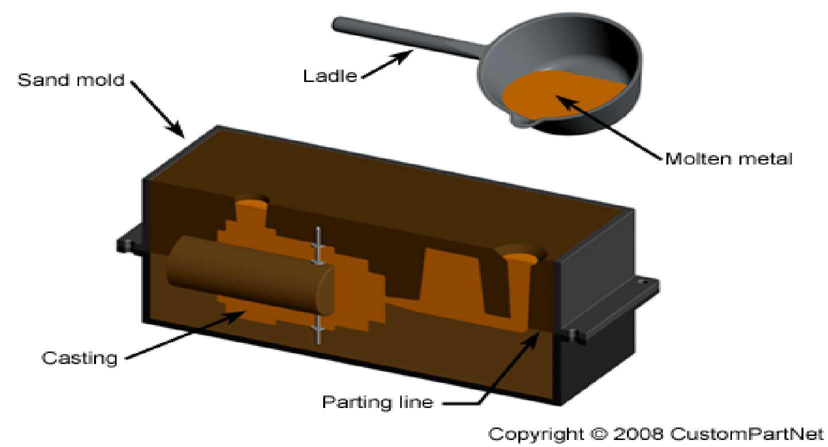
Melting ➔ Die/ Sand Mold Preparation ➔ Clamping ➔ Injection/ Pouring ➔ Cooling ➔ Ejection ➔ Trimming ➔ ~~Post-heat treatment~~

Die Casting



Source: www.cwmdiecast.com

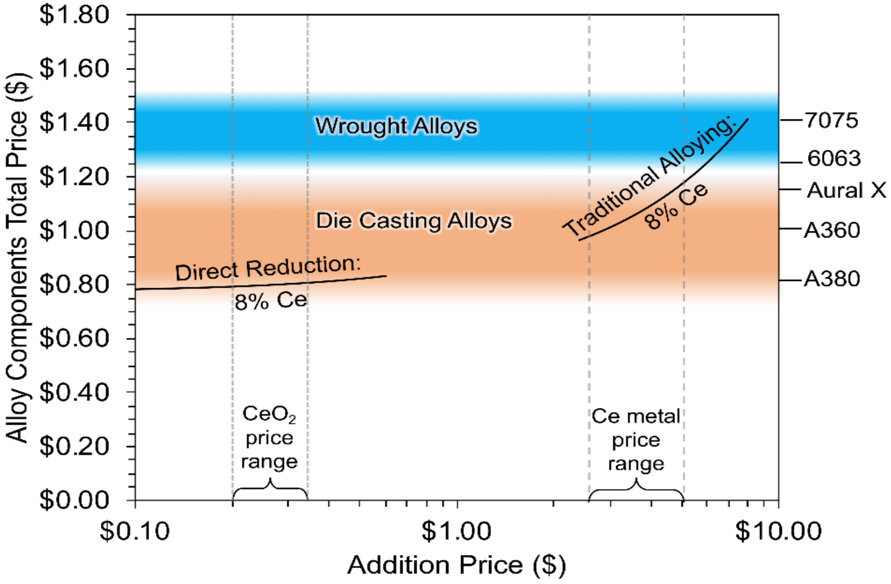
Sand Casting

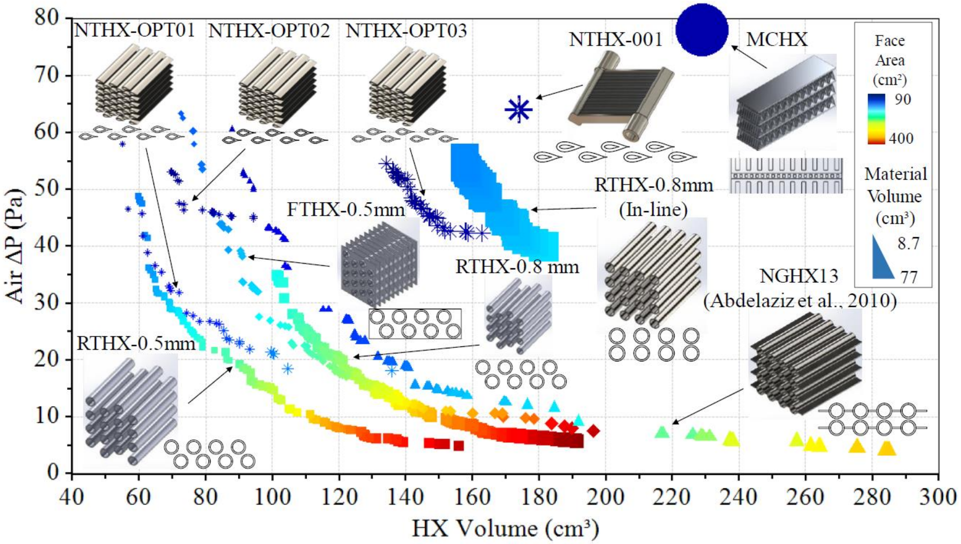


Estimated Costs (USD/lb)	Complete Cast		Headers Cast on Extruded Tubes	
HX Dimensions:	660 x 200 x 22 mm	1000 x 1000 x 22 mm	660 x 200 x 22 mm	1000 x 1000 x 22 mm
Sand Casting	4.95	3.62	5.86	4.55
Die Casting	2.51	2.22	3.05	3.05

Economics

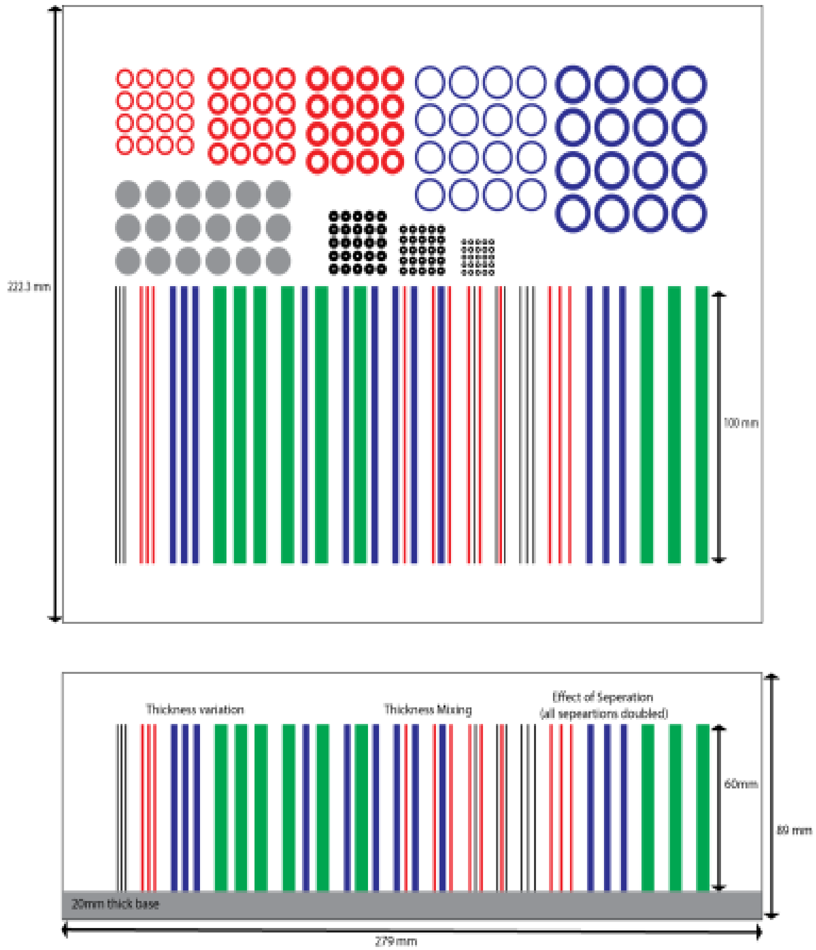
- Material cost is ***comparable to conventional aluminum alloys***
- ***Manufacturing costs are competitive***
- Future advanced heat exchangers can reduce material mass >50% for same performance
- If new, advanced HXs can be cast, realizing significant efficiency gains and/or cost savings

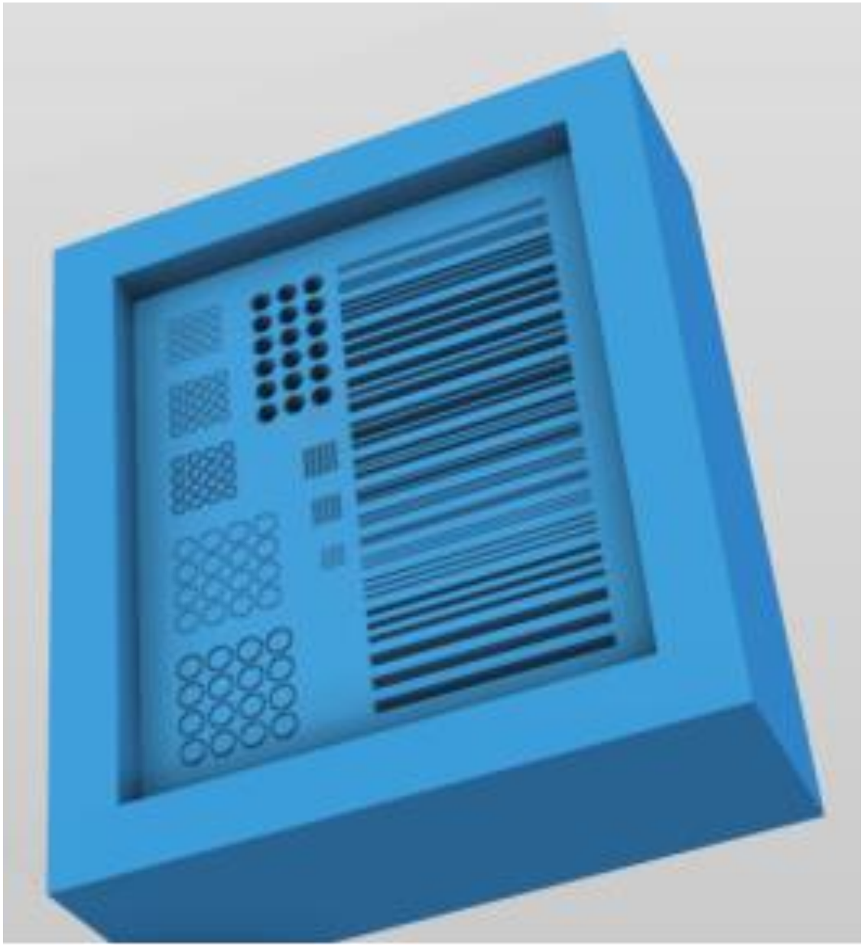




(Bacellar, 2016)

Progress: Finding the Design Boundaries





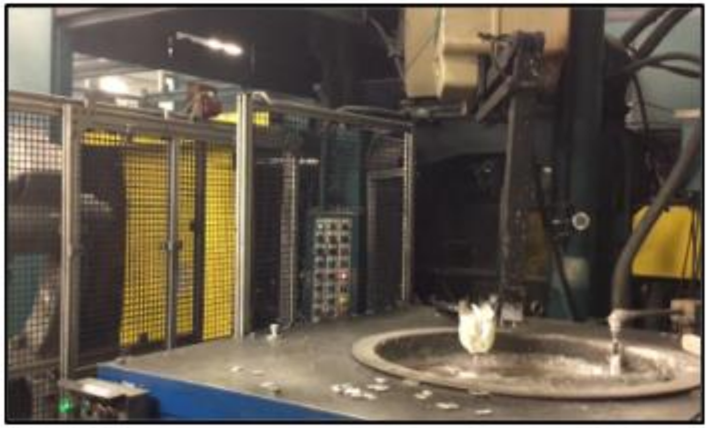
Investigating what geometries can be cast/identifying challenges.

Progress: Al-Ce Die Casting Trial Performed at Scale

- Die casting studies require near-scale or full-scale trials
- Ingots Cast at Eck Industries
- Trial performed at TTE in Oak Ridge

Eck Industries, Inc.
Specialists in Premium Aluminum Castings

TTE Tennessee Tool & Engineering



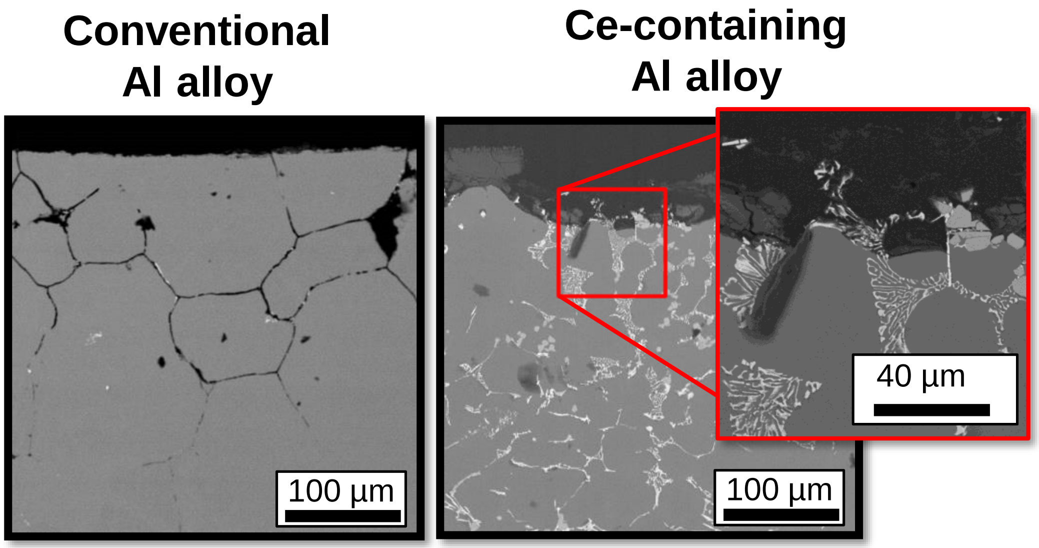
Feasibility of Al-Ce alloy die casting has been demonstrated

4,000 lb of ingots made for casting trial

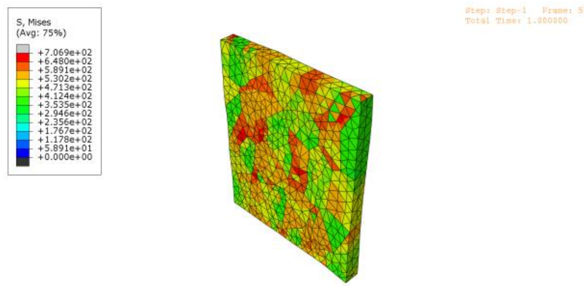
Has the potential to simplify the HX manufacturing process

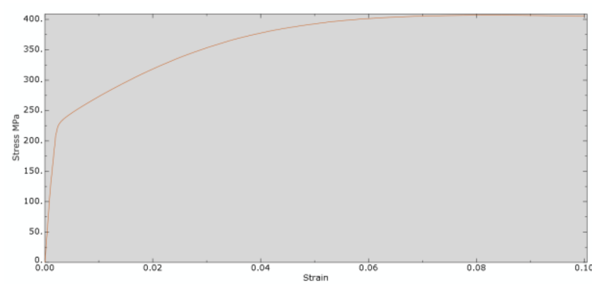
Progress: Current Focus (March–April)

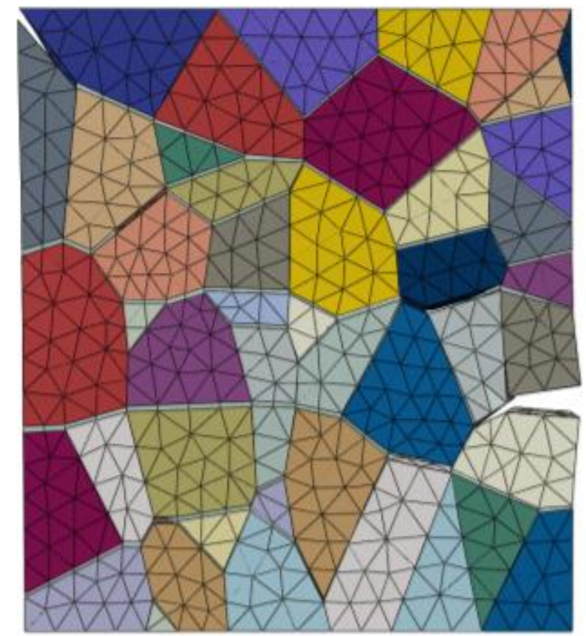
- **Completion of physical property measurements associated with Al-Ce casting**
- **Corrosion testing**
  - Intergranular and salt spray testing show significant improvement over conventional aluminum alloys
  - Currently looking at the resistance to sulfuric acid
- **First cast trial**



Progress: FEM Analysis on Supercomputer



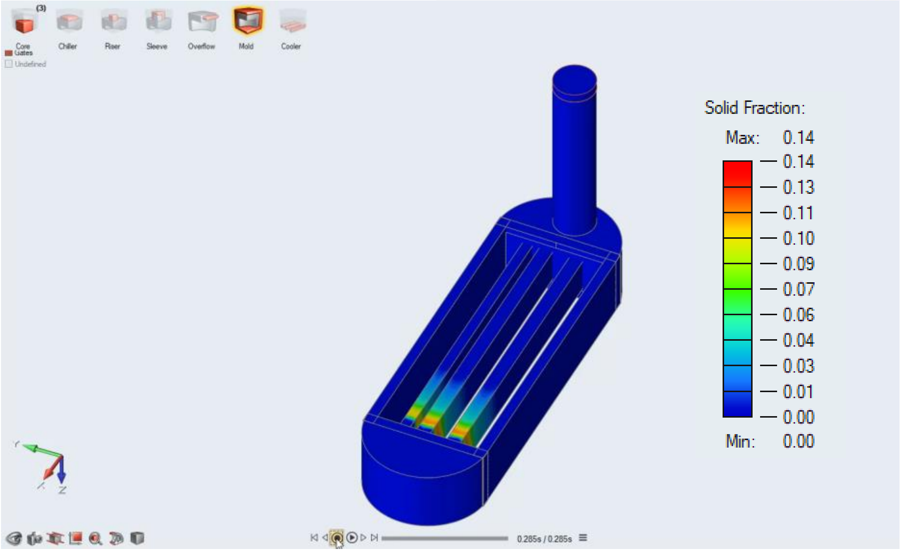




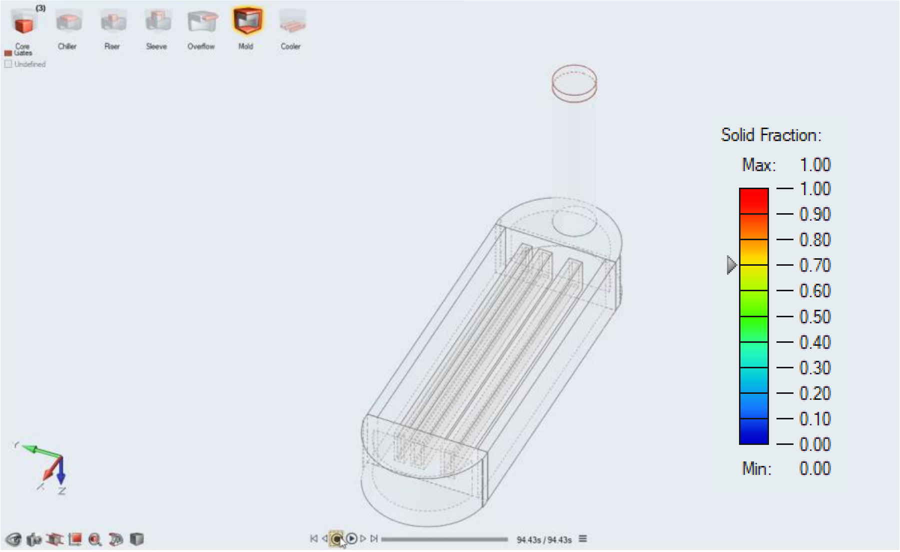
Developing the model that can simulate the grain boundary under stress. When combined with the experimental data, the result of such study can tell us:

- What quenching rate can make the alloys stronger
- What quenching temperature can help to reduce fatigue
- The solidification impact on the casting process
- The appropriate cast design
- How the casting parameters tie into the properties of the Al-Ce parts

Video of the stress in the y direction towards the end cracks will start to form throughout the model.



Solid fraction during cast filling (0=liquid).



Solid front during solidification (0=liquid).

Third Party Evaluation: Preliminary Ranking on Applications

- 1—most favorable, 5—least favorable

Application	Heat Exchanger Manufacturability	Charge/ Leak Reduction Potential	Non-Energy Benefit	HX Market Size	Energy Saving Potential	Overall Score (Rank)
Residential AC/HP	3	3	4	1	1	12 (1)
Gas-Fired Furnaces	2	5	2	3	1	13 (2)
Gas-Fired Water Heating	1	5	3	2	2	13 (2)
Commercial AC/HP	3	2	4	3	3	15 (4)
Electric Water Heating	2	3	3	4	3	15 (4)
Commercial Refrigeration	4	1	3	4	4	16 (6)
Residential Clothes Drying	2	3	3	4	4	16 (6)

Progress: Stakeholder Engagement

Engagement:

Weekly meetings: ORNL-VT

Biweekly meetings: ORNL/ECK/UMD/VT/OTS

Publications/Inventions/Reports:

Invention Disclosure 201804134, DOE S-138,801

Completed the 3rd party market evaluation report

Industry input:

Optimized Thermal Systems

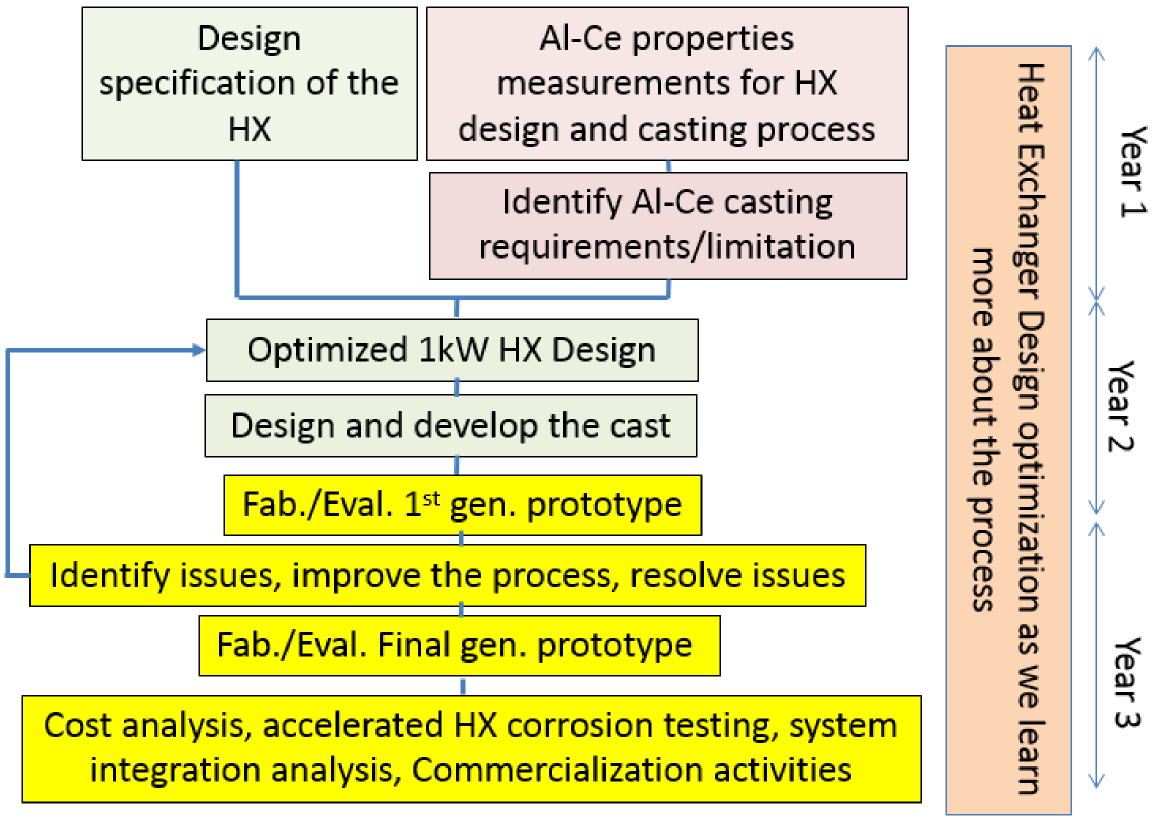
Heat Transfer Technologies

Eck Industries, Inc. Specialists in premium aluminum castings

SHILOH

Remaining Project Work

- Identify Al-Ce casting limitations
- Design and develop 1 kW HX cast
- Fabrication and evaluation
- Improvements
- Cost analysis and accelerated life testing/commercialization activities



Thank You

Oak Ridge National Lab/ECK/Virginia Tech./UMD
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REFERENCE SLIDES

Project Budget

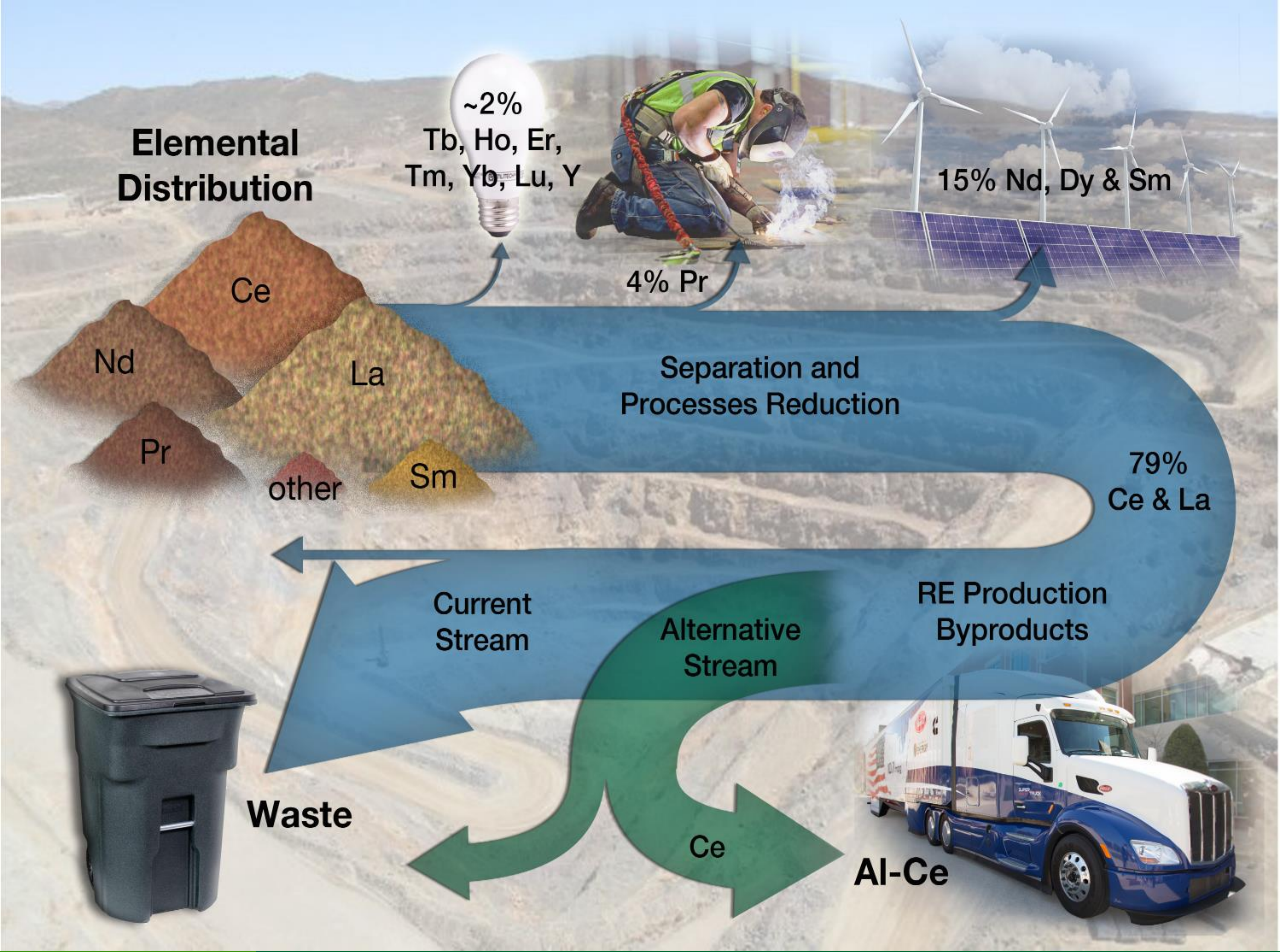
Project Budget: $1,327K (open lab call 2018)
Variances: None
Cost to Date: $139K (Through March 2019)
Additional Funding: No additional direct funding

Budget History					
10/1/2018 (past)		FY 2019 (current)		FY 2020 – 9/31/2020 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
		$443k	$10k	$443k	$20k

Project Plan and Schedule

Project Schedule		
Project Start: 10/1/2018		Completed Work
Projected End: 9/31/2021		Active Task (in progress work)
		Milestone/Deliverable (Originally Planned) use for missed
		Milestone/Deliverable (Actual) use when met on time

	FY2013				FY2014				FY2015			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work												
Q1: Market assessment												
Q2: Property measurments												
Q3: HX design specifications												
Q4: HX design showing 15% improvement												
Q1: Design the cast												
Q2: Complete CFD simulation												
Q3: Complete cast fabrication												
Q4: Evaluate the cast HX performance												
Q1: Documenting the manufacturing flaws												
Q2: Complete the fabrication of second HX												
Q3: Evaluate the thermal performance												
Q4: Cost analysis, commercialization activities, report												

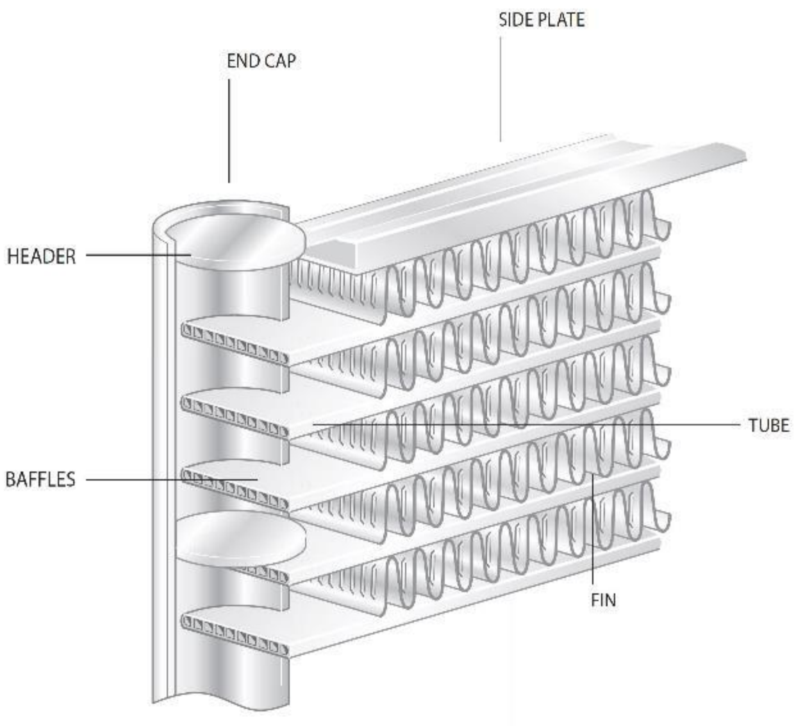


Elemental Distribution
~2%
Tb, Ho, Er, Tm, Yb, Lu, Y
4% Pr
15% Nd, Dy & Sm
Ce
Nd
La
Pr
other
Sm
Separation and Processes Reduction
79% Ce & La
Current Stream
Alternative Stream
RE Production Byproducts
Waste
Ce
Al-Ce

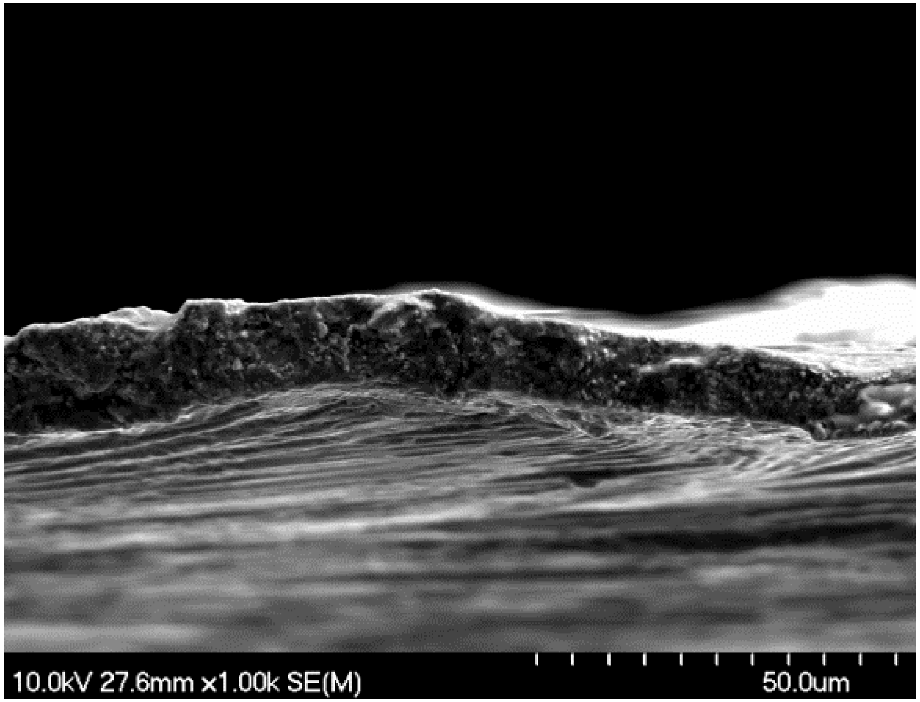
Energy Impact

Application	Annual Energy Consumption (2030)	Estimated Efficiency Gain	Potential Energy Savings [Quads]
Residential AC/HP	2.413	10%	0.241
Commercial AC/HP	1.030	10%	0.103
Electric Water Heating	1.370	10%	0.137
Gas-fired Water Heating	1.644	10%	0.164
Gas-Fired Furnaces	3.559	10%	0.356
Commercial Refrigeration (condensers only)	1.747	5%	0.087
Residential Clothes Drying	0.660	10%	0.066
Total			**1.155**

Progress:



Al microchannel heat exchangers are currently made via expensive injection molding. Corrosion is an issue for them (because passages become clogged).



On April 13,2018, we demonstrated high-aspect-ratio features that are less than 10 microns thick cast directly from molten Al-Ce-X.