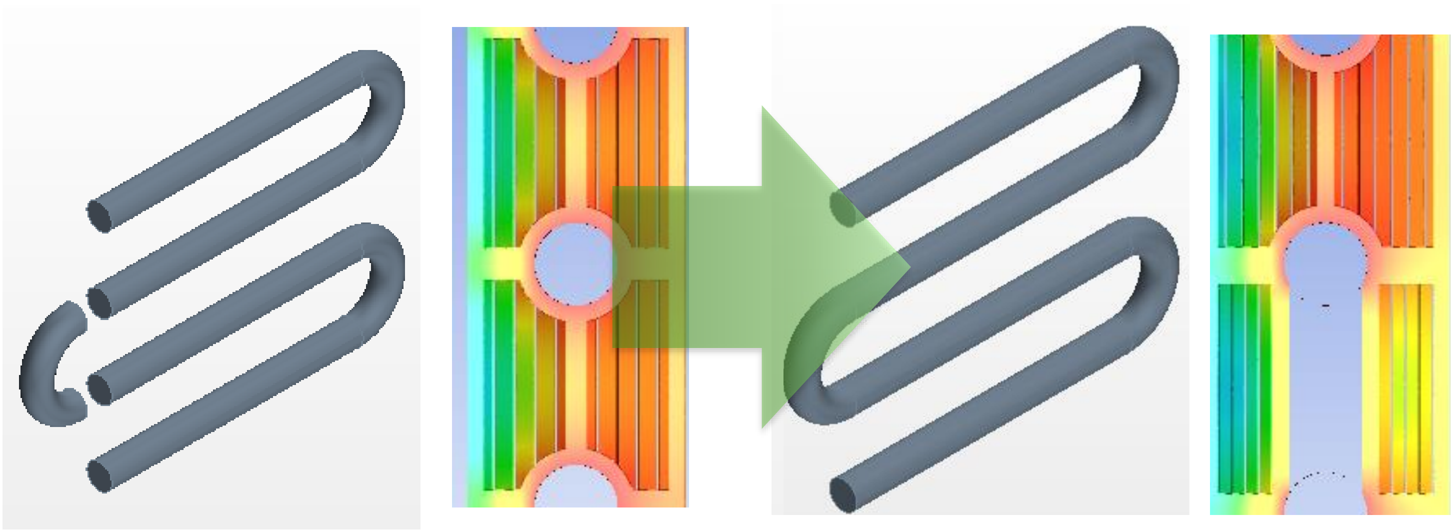
U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Advanced Serpentine Heat Exchangers



Optimized Thermal Systems, Inc.
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Optimized Thermal SYSTEMS

Project Summary

Timeline:

Start date: 10/2016

Planned end date: 10/2019 ***(04/2020)***

Key Milestones

1. Develop Optimized Fin Geometry; 08/2017
2. Construct Prototype Heat Exchangers; 03/2018
3. Commercialization Plan; 10/2019

Key Partners:

Optimized Thermal Systems, Inc. (OTS)
Heat Transfer Technologies, LLC (HTT)
United Technologies Research Center (UTRC)

Budget:

Total Project $ to Date: $299,366

- DOE: $238,293
- Cost Share: $61,073

Total Project $: 663,397

- DOE: $509,563
- Cost Share: $153,834

Project Outcome:

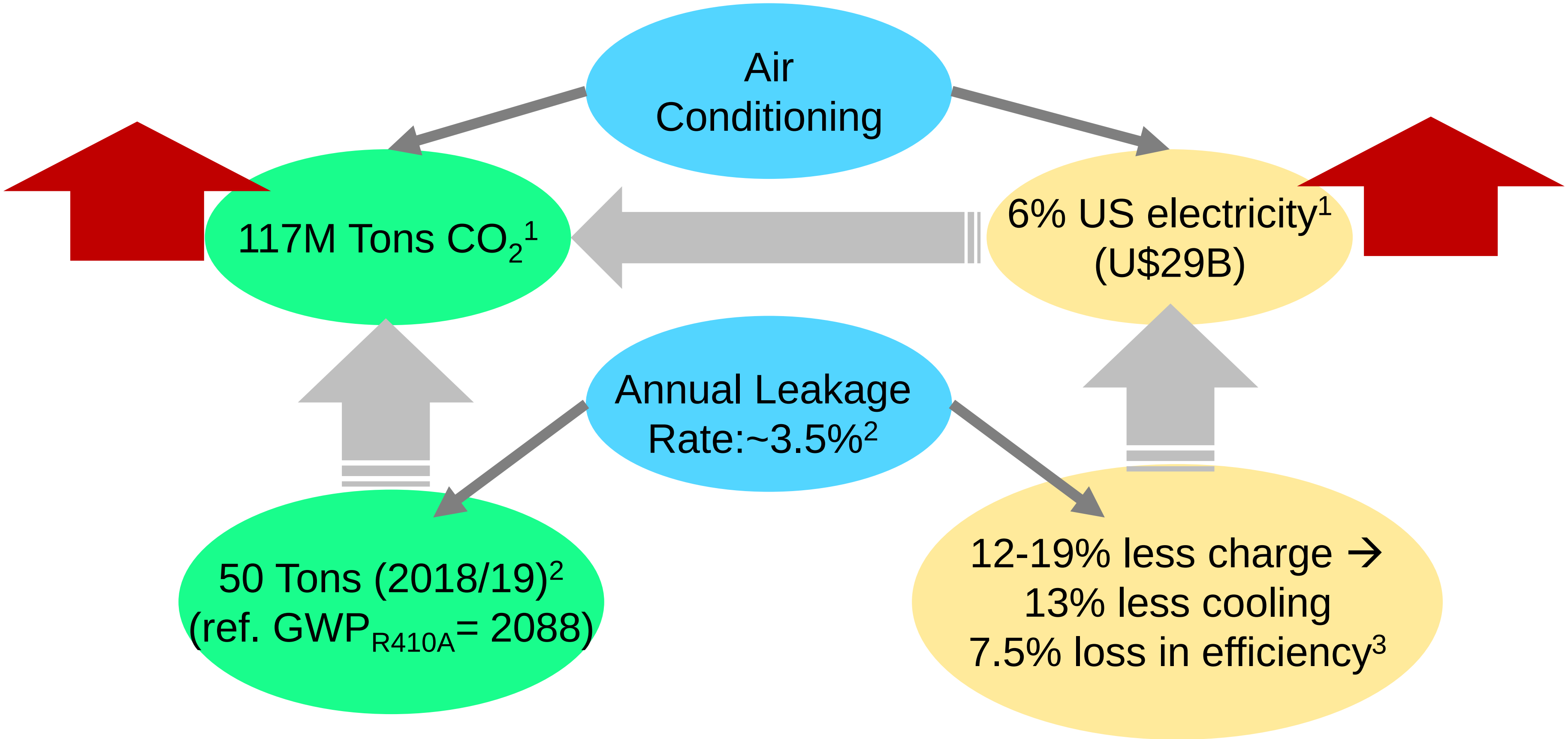
Conceptualize **serpentine heat exchangers** for HVAC application, aiming for **leakage reduction**.

Design & Optimize novel “dog-bone” fin concepts that result in **equivalent or better performance** than current state-of-the-art tube-fin heat exchangers.

Prototype, validate and commercialize.

Challenge

Problem Definition: refrigerant leakage in heat pumps and air conditioners has major impact, directly and indirectly, on both energy consumption and environment.



Focus of this project: Brazed joints → vulnerable locations; prone to leakage

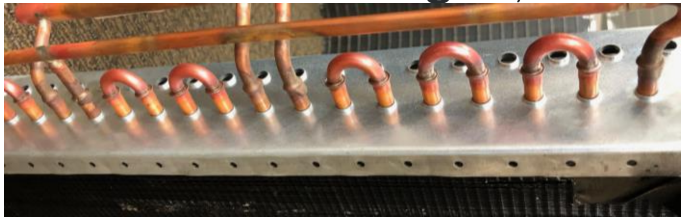
[1] https://www.energy.gov/energysaver/home-cooling-systems/air-conditioning (accessed on: 04/05/18)

[2] Impacts of Leakage from Refrigerants in Heat Pumps. Report prepared for the U.S. DOE by the London Southbank University, March 2014.

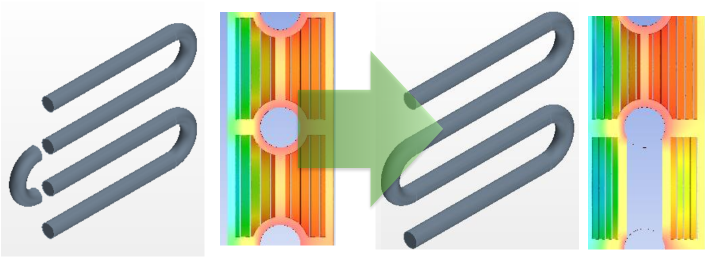
[3] Kim, W. Braun, J.E. Impacts of Refrigerant Charge on Air Conditioner and Heat Pump Performance. International Refrigeration and Air Conditioning Conference at Purdue, July 10-15, 2010

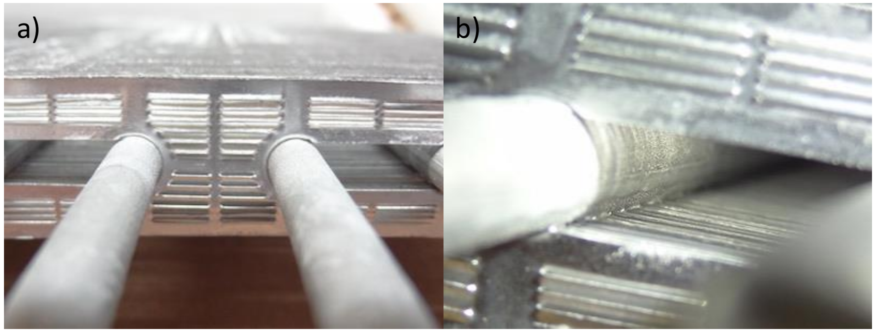
Objectives

- Eliminate 70%-85% of the joints in one, or both heat exchangers, of a 3-ton residential AC / heat pump system

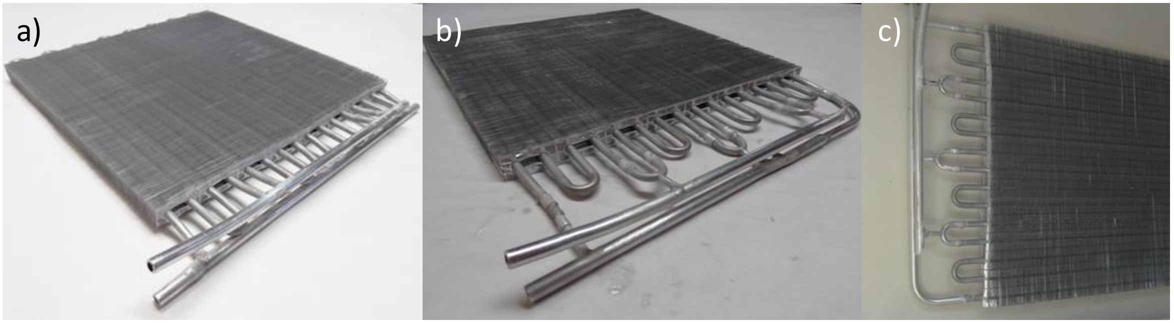


- Develop serpentine heat exchangers (SHX) with enhanced “dog-bone” fins resulting in equivalent, or better performance than current state-of-the-art HX’s
  - Overcome surface area reduction
  - Reduce / eliminate contact resistance





- Develop a cost-effective product and manufacturing means for mass production



Team

Key Partners

Heat Transfer Technologies LLC

Manufacturing solutions
Small scale prototyping
Brazing / Soldering / Welding
Vendor management / POC
Market analysis

Optimized Thermal Systems

HX / System Design Optimization
(CoilDesigner®, VapCyc® CFD, MOGA)
Performance Tests (wind-tunnel / env. chamber)
Data Analysis / Post-Processing
Decision Making (Technical / Management)

United Technologies Research Center

Manufacturing solutions
Larger scale manufacturing resources
Market analysis
Product dev. /commercialization

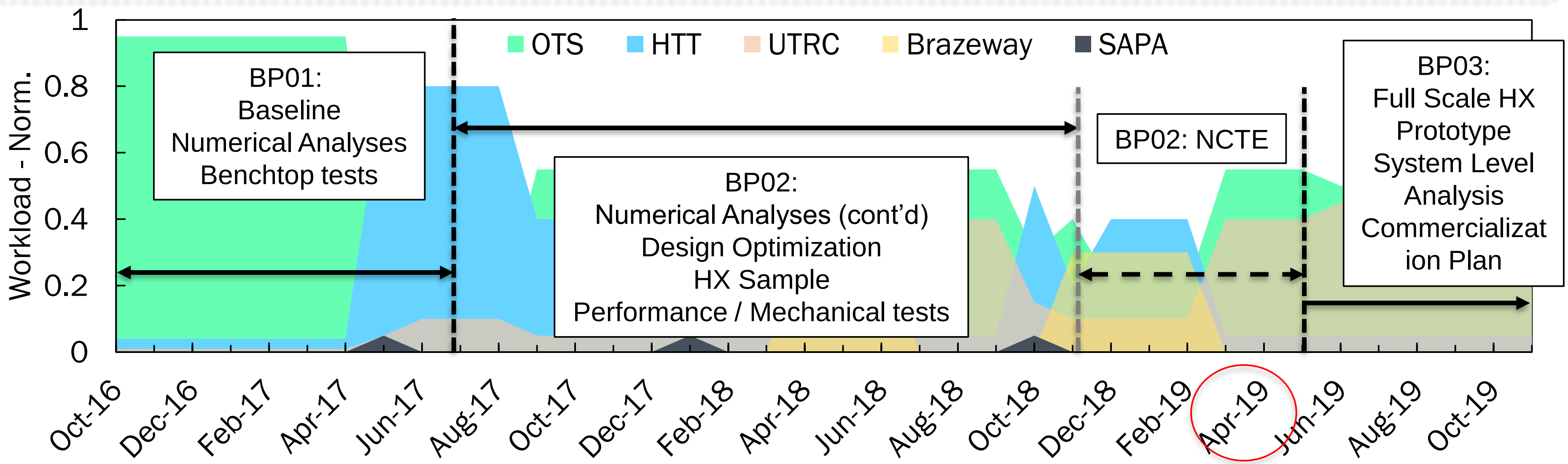
Key Vendors

BRAZEWAY

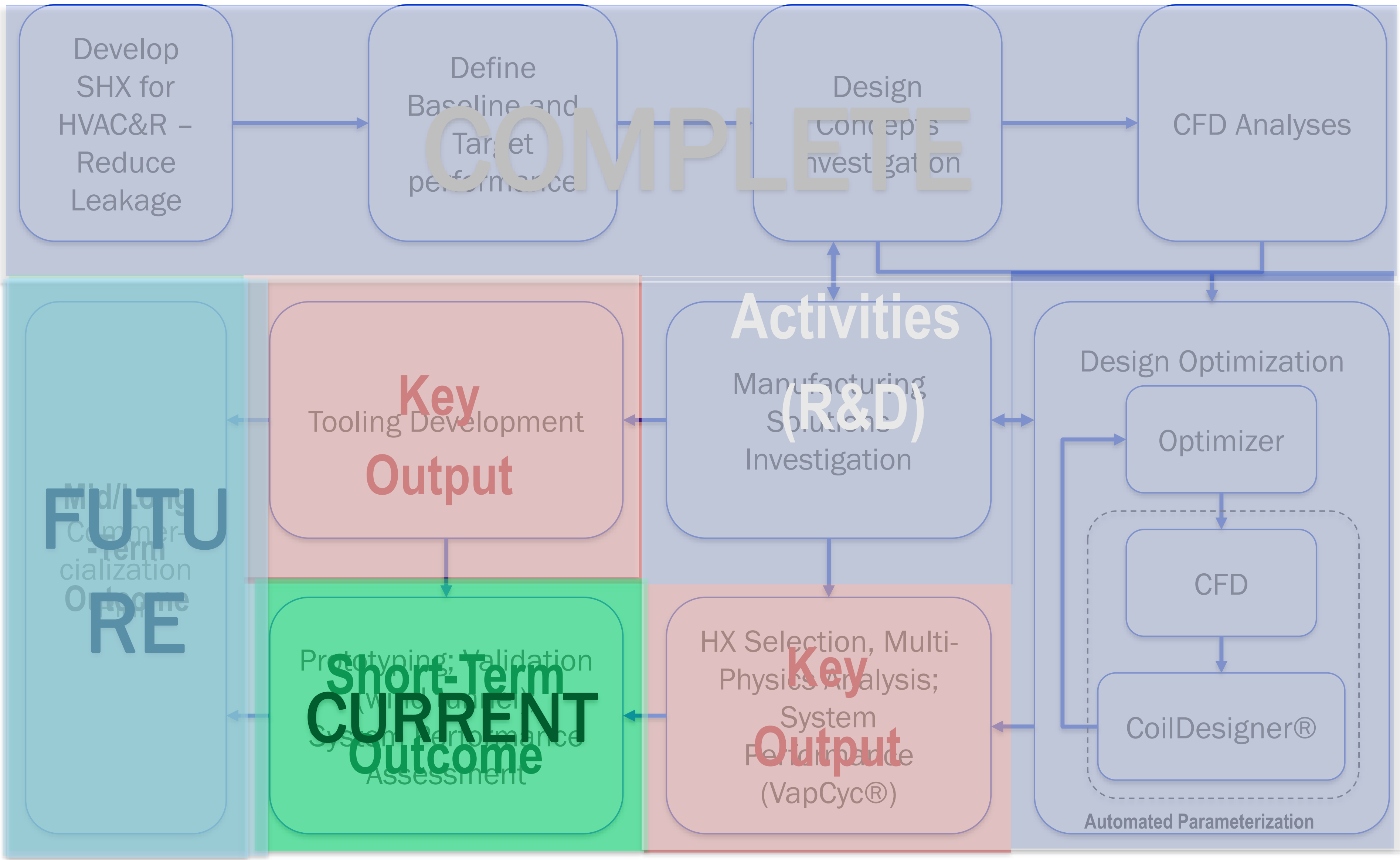
Fin tooling / Serpentines
Fin-tube Assembly

sapa:

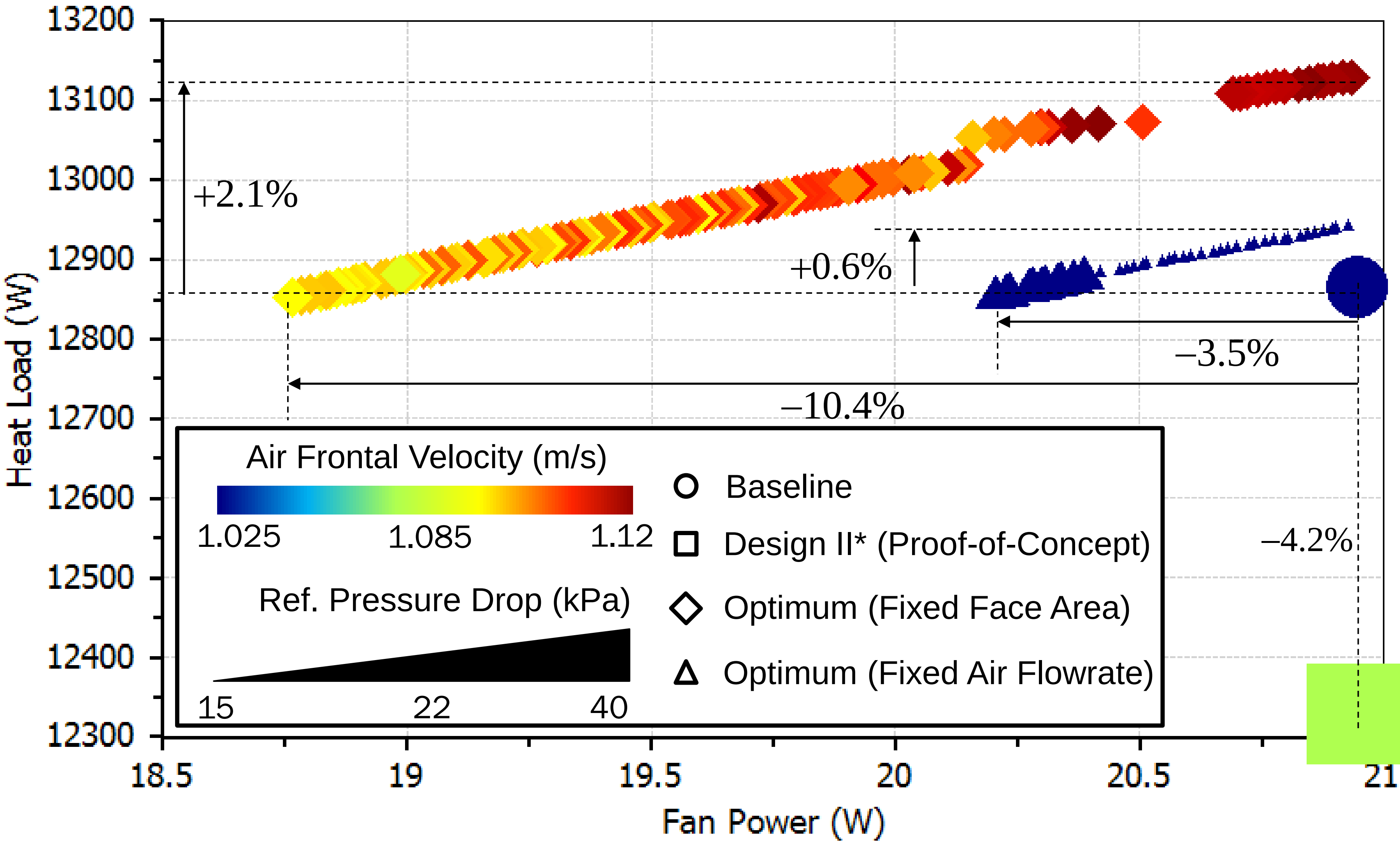
Clad aluminum tube supplier



Approach Framework

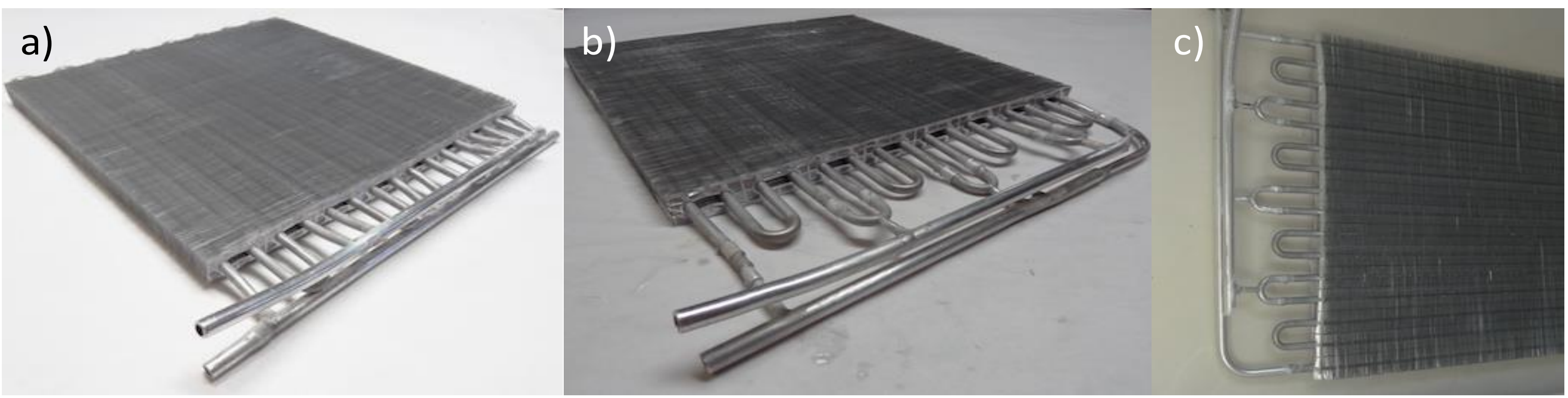


R410A Condenser Optimization Results



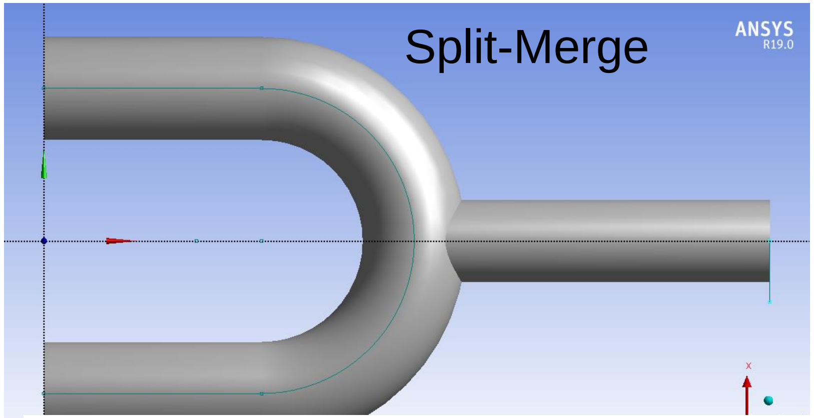
Design II Sample 1’x1’ Prototypes

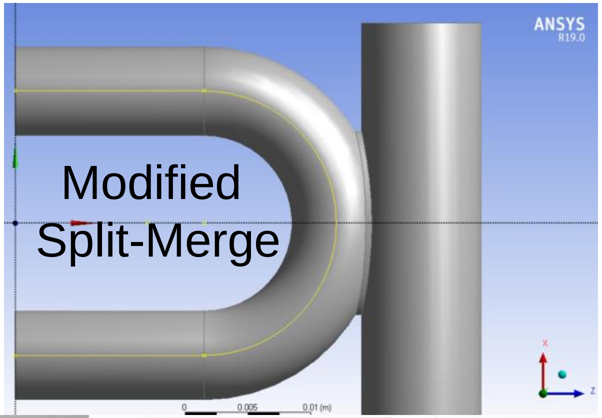
Prototype #	# Fins	Finned Length mm	FPI	Remarks	Observation	Circuit
HX1	253	320	20.0	Re-flare fin collar	~5% non brazed fins	Conventional
Equivalent Coils		320	19.2	Re-flare fin collar	~5% non brazed fins	Split-Merge
HX3	253	320	20.0	Re-flare fin collar	~5% non brazed fins	Split-Merge
HX4	274	297	21.7	No re-flare	**<1% non brazed fins**	**Modified Split-Merge**



Prototypes with manifolds: a) HX1; b) HX2; c) HX3

Split-Merge Connections

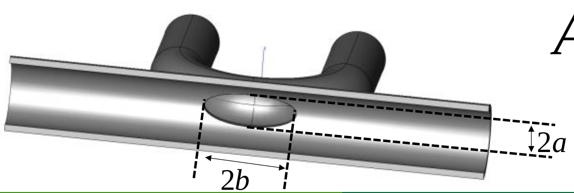


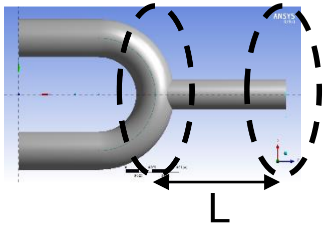


Original Split-Merge (SM): $b_{orig\_sm} = a_{orig\_sm}$

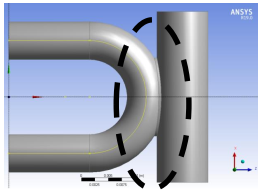
Modified SM: $a_{\mathrm{mod}\_sm} = a_{orig\_sm} = a$

Cross-section Areas: $$\frac{A_{cs\_\mathrm{mod}\_sm}}{A_{cs\_orig\_sm}} = \frac{b_{\mathrm{mod}\_sm}}{a}$$





2 Restrictions:
1 contraction,
1 expansion

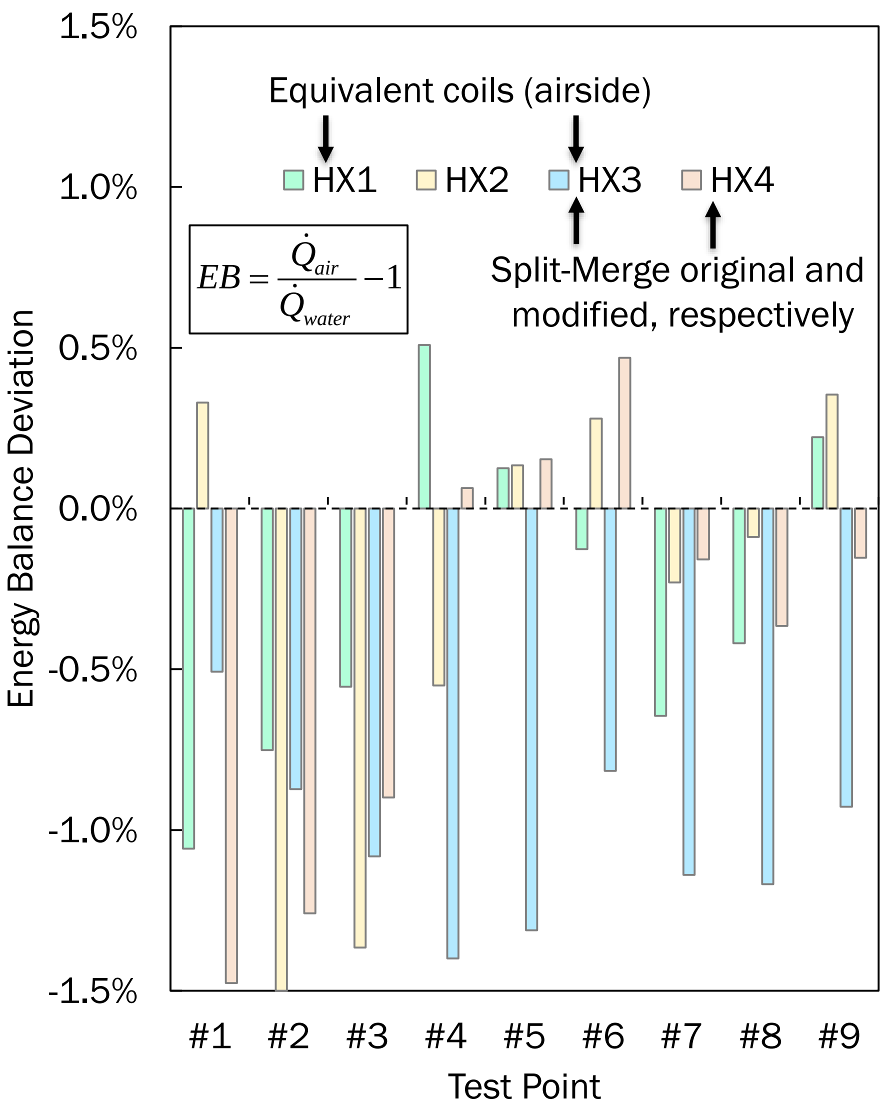


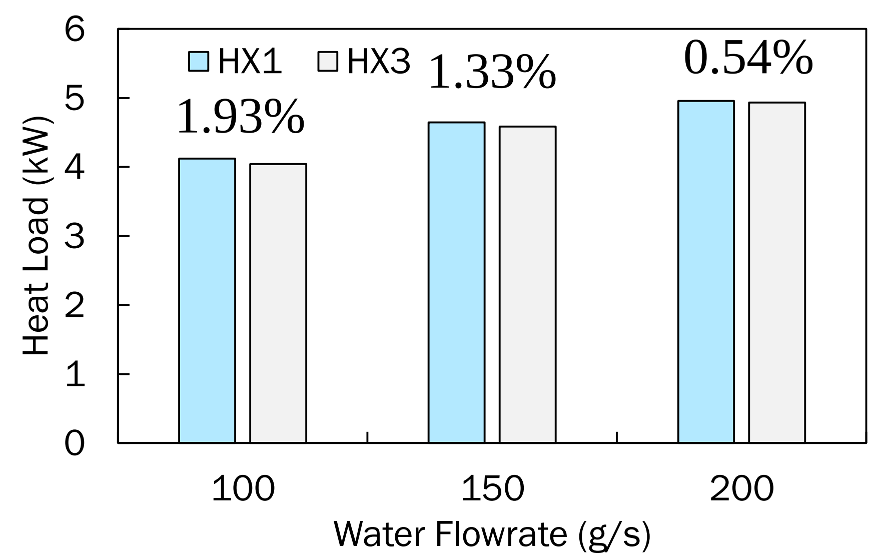
1 Restriction:
single expansion

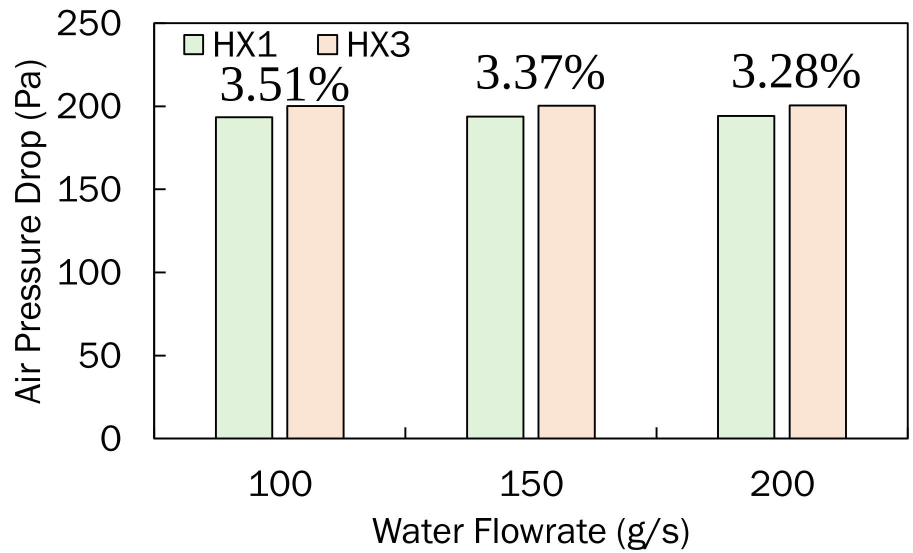
Hot-Water Performance Tests (Validation Purposes)

Air Inlet Temp.	Air Flow Rate	Water Inlet Temp.	Water Flow Rate
°C	cfm	°C	g/s
16	500, 1000, 1500	50	100, 150, 200

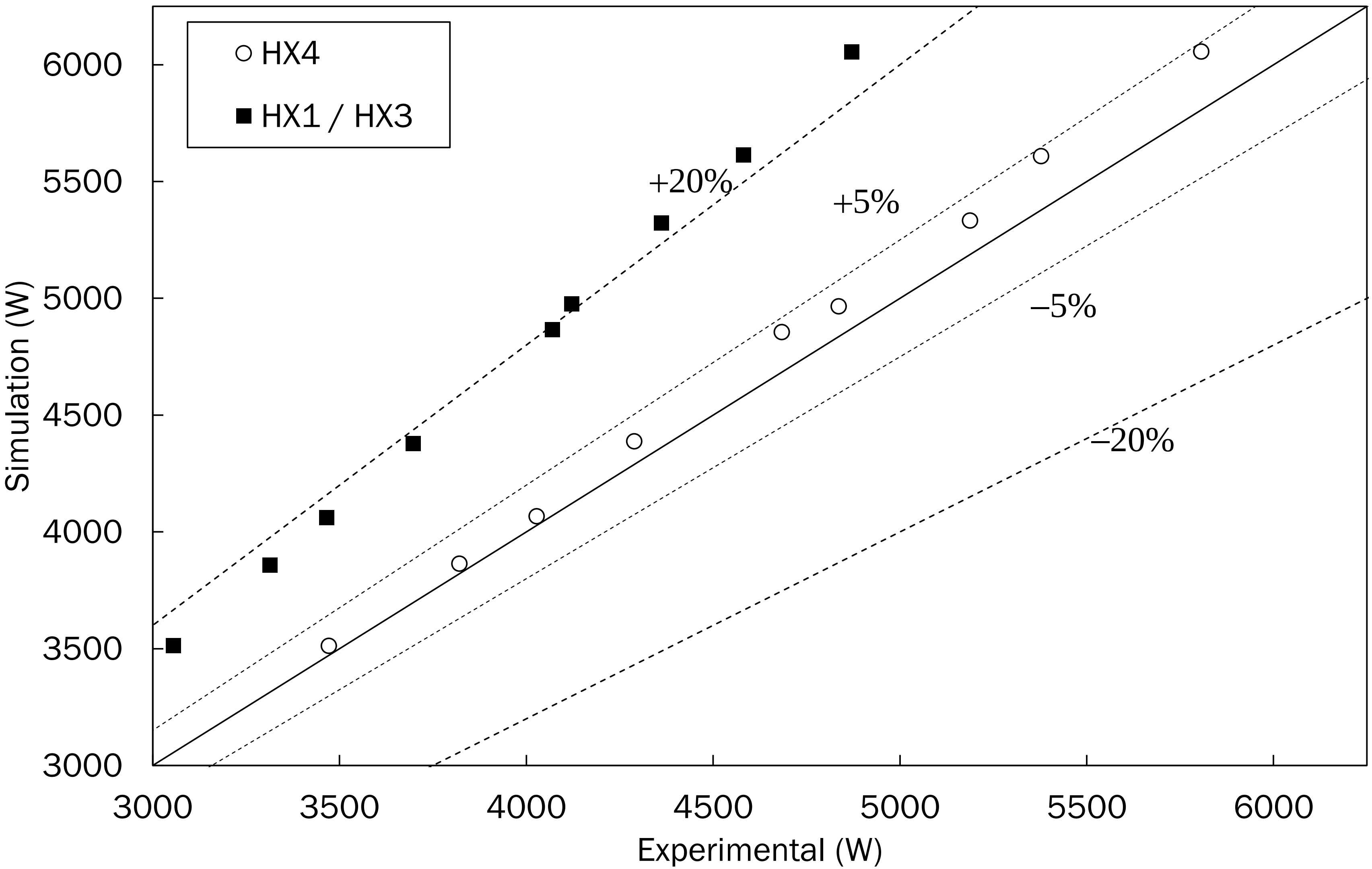
Test Results & Validation



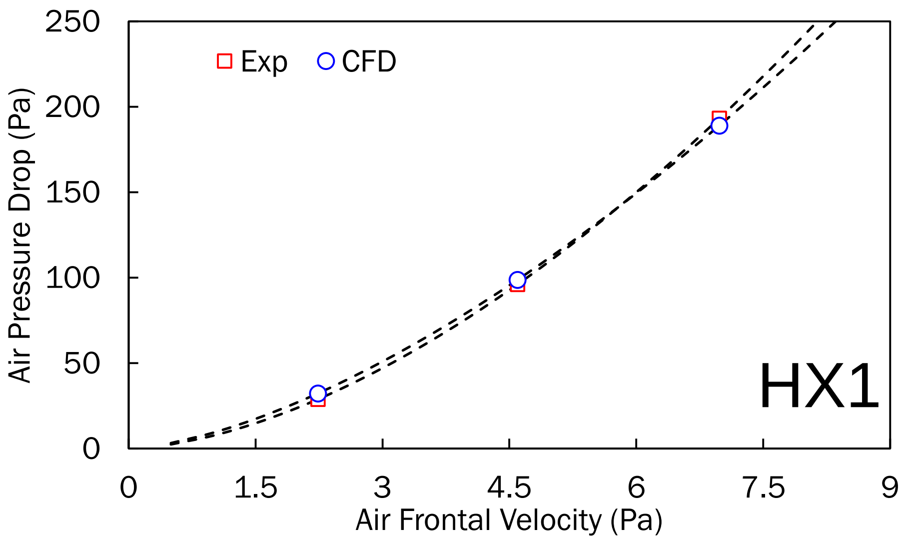


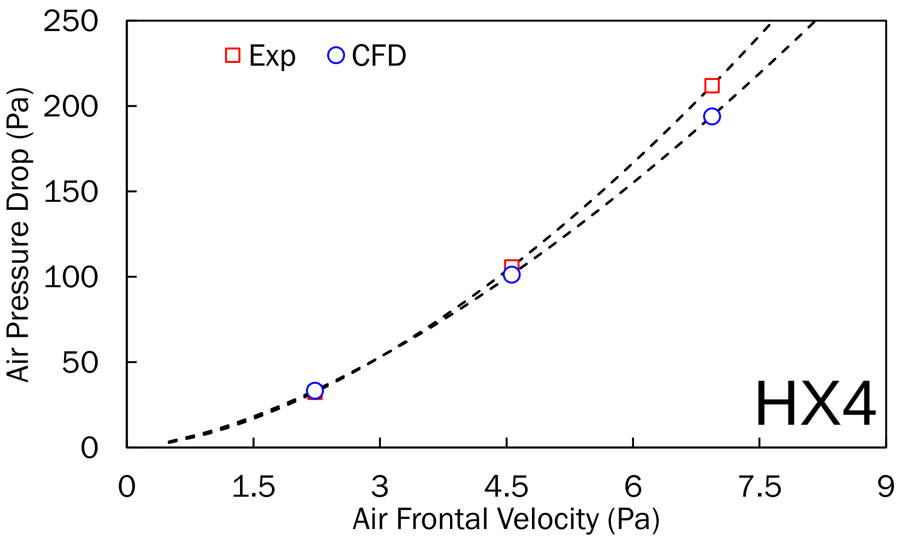


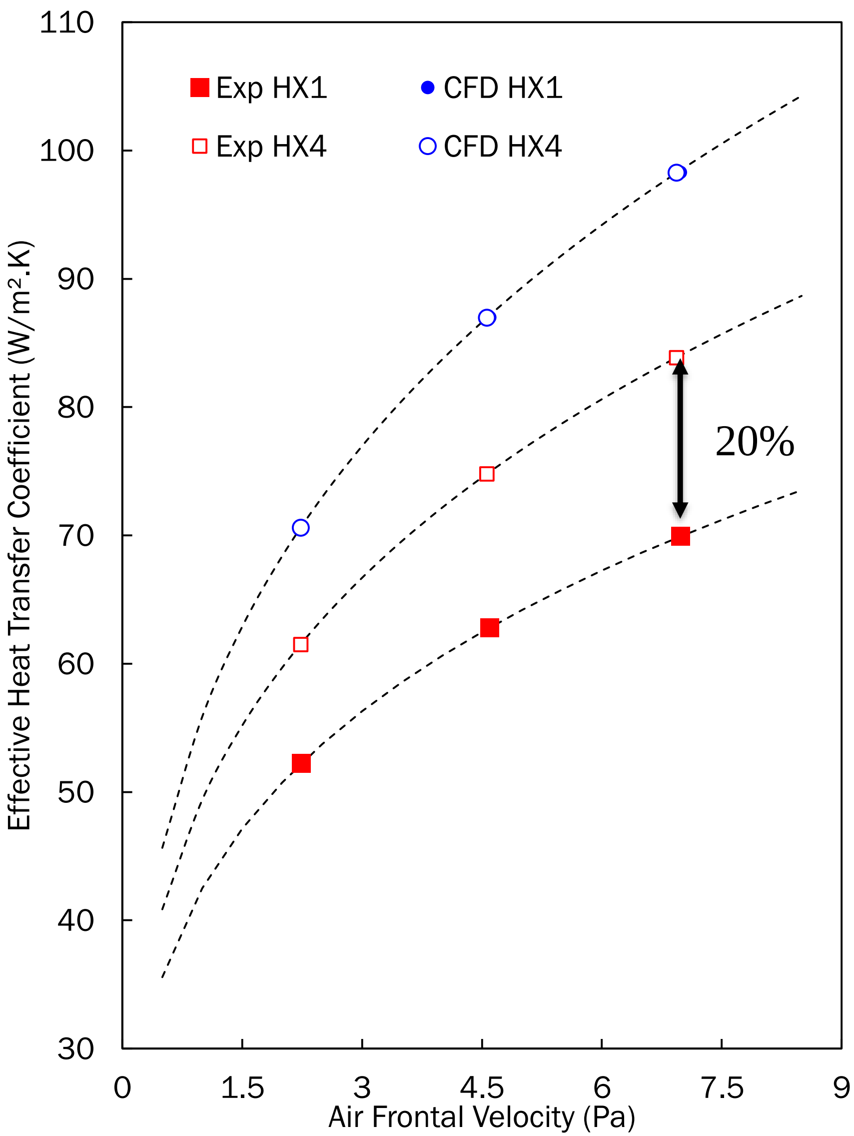
Verification & Validation



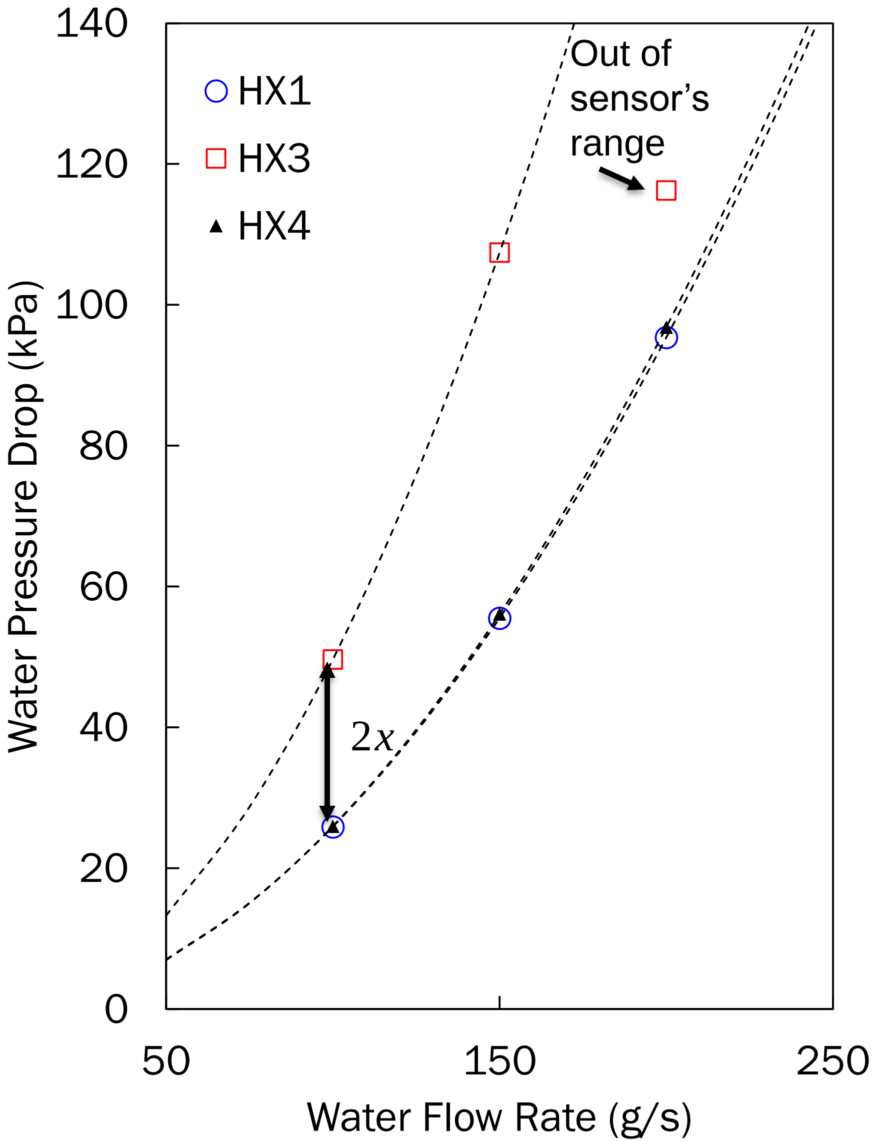
Verification & Validation

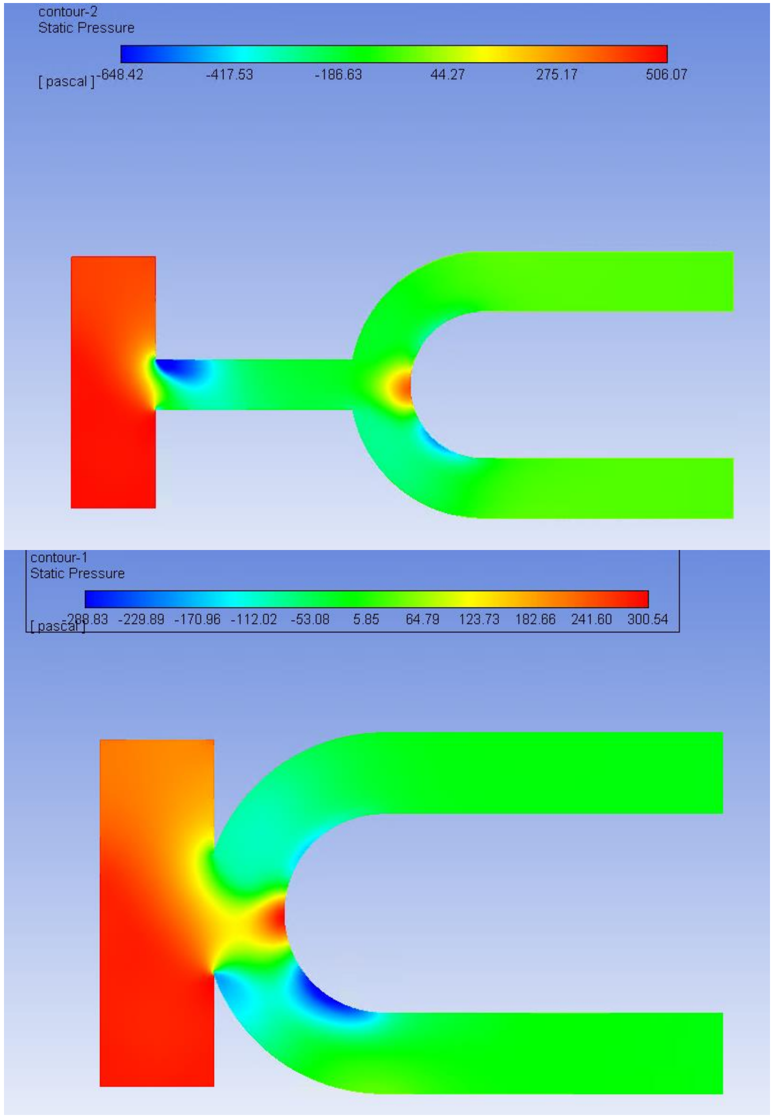




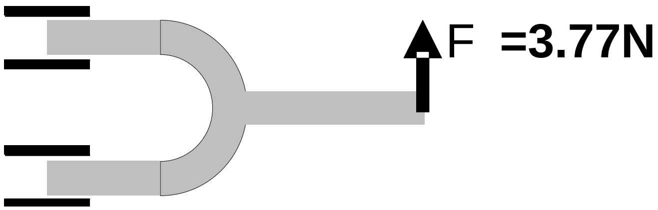


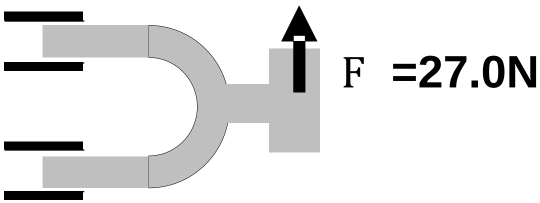
Water-Side Pressure Drop

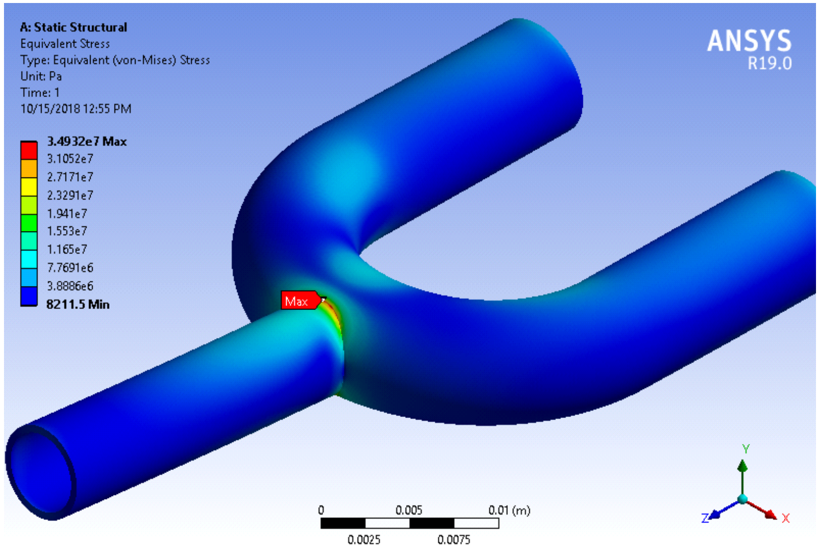


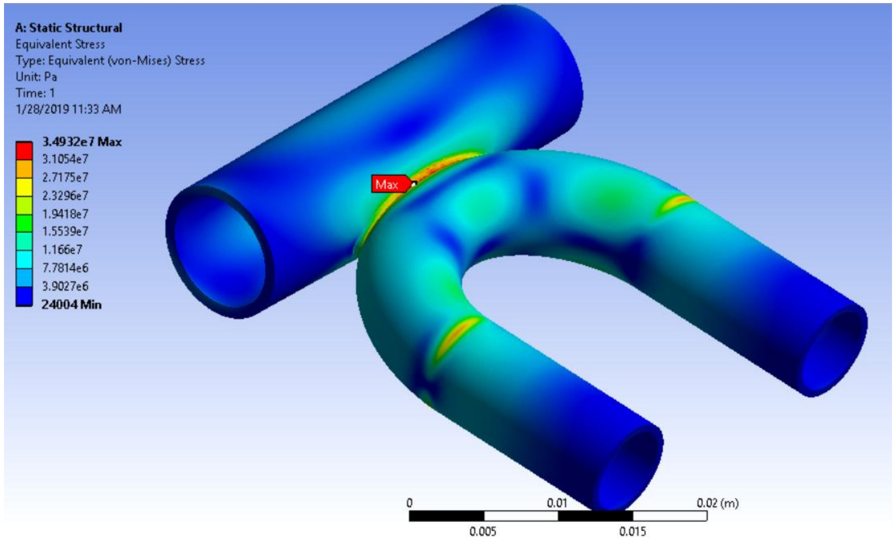


FEA Analysis – Max Load Until Yield









Conclusions

- **Optimization suggests max. 2% more capacity or 10% pumping power over baseline**
- **Fin tooling and brazing used to successfully build 4 prototypes**
- **Performance tests**
  - HX1 and HX3 demonstrated good repeatability
  - Air pressure drop prediction within 10%
  - Model consistently overpredicted thermal performance for HX3, resulting in more than 30% deviation in heat transfer coefficient (HTC)

Conclusions (cont'd)

- **Performance tests (cont'd)**
  - HX4 matched model within 5% in capacity, with HTC overpredicted by 10-15%
  - Given good pressure drop prediction, numerical issues are less likely to be the main cause for the deviations found
  - Unaccounted thermal resistances play a major role in the deviation
  - Non-brazed fins add considerable contact resistance
  - Tolerance differences should improve successful brazing joints, thus reducing considerably the contact resistance
  - Original Split-Merge joint added a factor of two in pressure drop, however the modified version is equivalent to conventional circuiting
- **Mechanical tests**
  - The remaining task in BP02 will be finalized in 04/2019 and 05/2019 coinciding with the end of budget period
  - Accurate assessment of number of non-brazed joints

Thank You

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Project Budget

- Under budget due to reduced need for subcontractors
- Budget reductions have enabled modest changes in prototype approach for additional development
- No other funding sources

	Budget History					
	BP1: Completed 10/2016 – 08/2017		BP2: To Date 08/2017 – 05/2019		BP3: Planned 05/2019 – 04/2020	
	DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
Budget	$100,432	$25,297	$253,488	$68,230	$155,643	$60,307
Actual	$69,992	$18,825	$168,301	$42,248	-	-

Project Plan and Schedule

Project Schedule		
Project Start: 10/2016		Completed Work
Projected End: 10/2019 (04/2020)		Active Task (in progress work)
	◆	Milestone/Deliverable (Originally Planned) use for missed
	◆	Milestone/Deliverable (Actual)

	FY2017				FY2018				FY2019				FY2020			
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)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work									NCTE							
1.0 Intellectual Property (IP) Management Plan																
2.1 Baseline Selection																
2.2 Initial Performance Simulations																
2.3 Material Simulation and Selection																
2.4 Benchtop Testing of Brazing Methods																
3.1 Optimization Definition and Manufacturing Considerations																
3.2 Develop Optimized Fin Geometry																
4.1 Design Fin Tooling																
4.2 Construct Prototype Heat Exchangers																
5.1 Heat Exchanger Performance Testing																
Current/Future Work																
5.2 Mechanical / Cyclic Testing																
6.1 Improve Manufacturing Techniques in Preparation for Commercialization																
6.2 System Level Integration																
6.3 System Level Testing																
7.0 Develop Technology to Market Commercialization Plan																