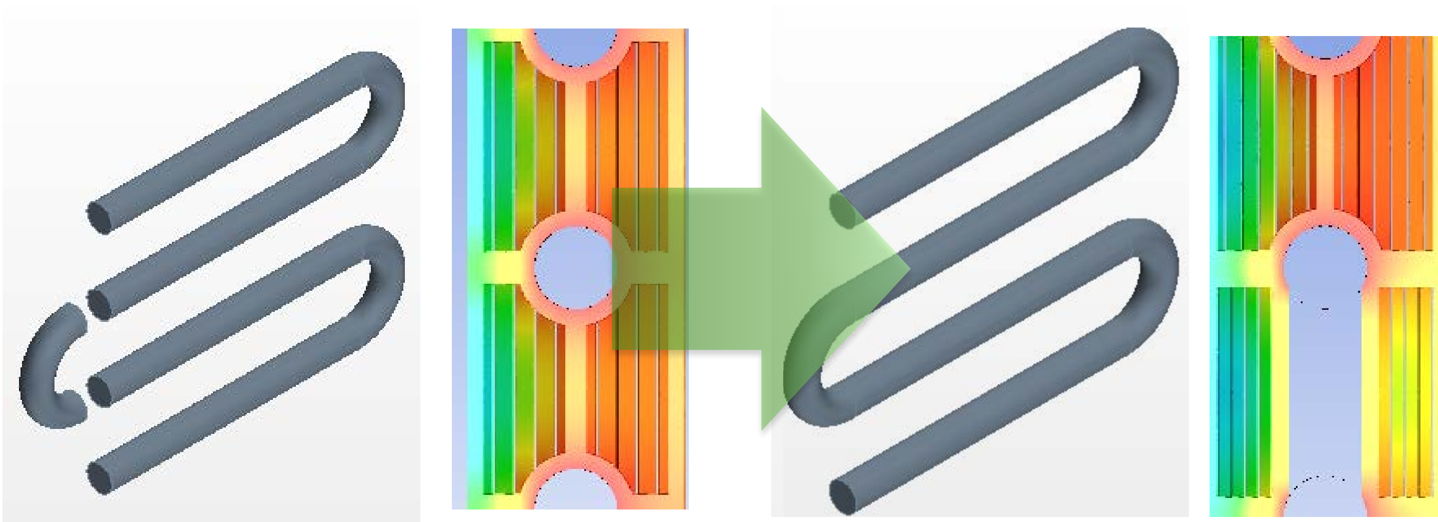
U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Advanced Serpentine Heat Exchangers



Optimized Thermal Systems, Inc.
Dr. Daniel Bacellar
bacellar@optimizedthermalsystems.com

Optimized Thermal SYSTEMS

Project Summary

Timeline:

Start date: 10/2016

Planned end date: 10/2019

Key Milestones

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

Budget:

Total Project $ to Date: $180,009

- DOE: $143,293
- Cost Share: $36,716

Total Project $: 663,397

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

Key Partners:

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

Project Outcome:

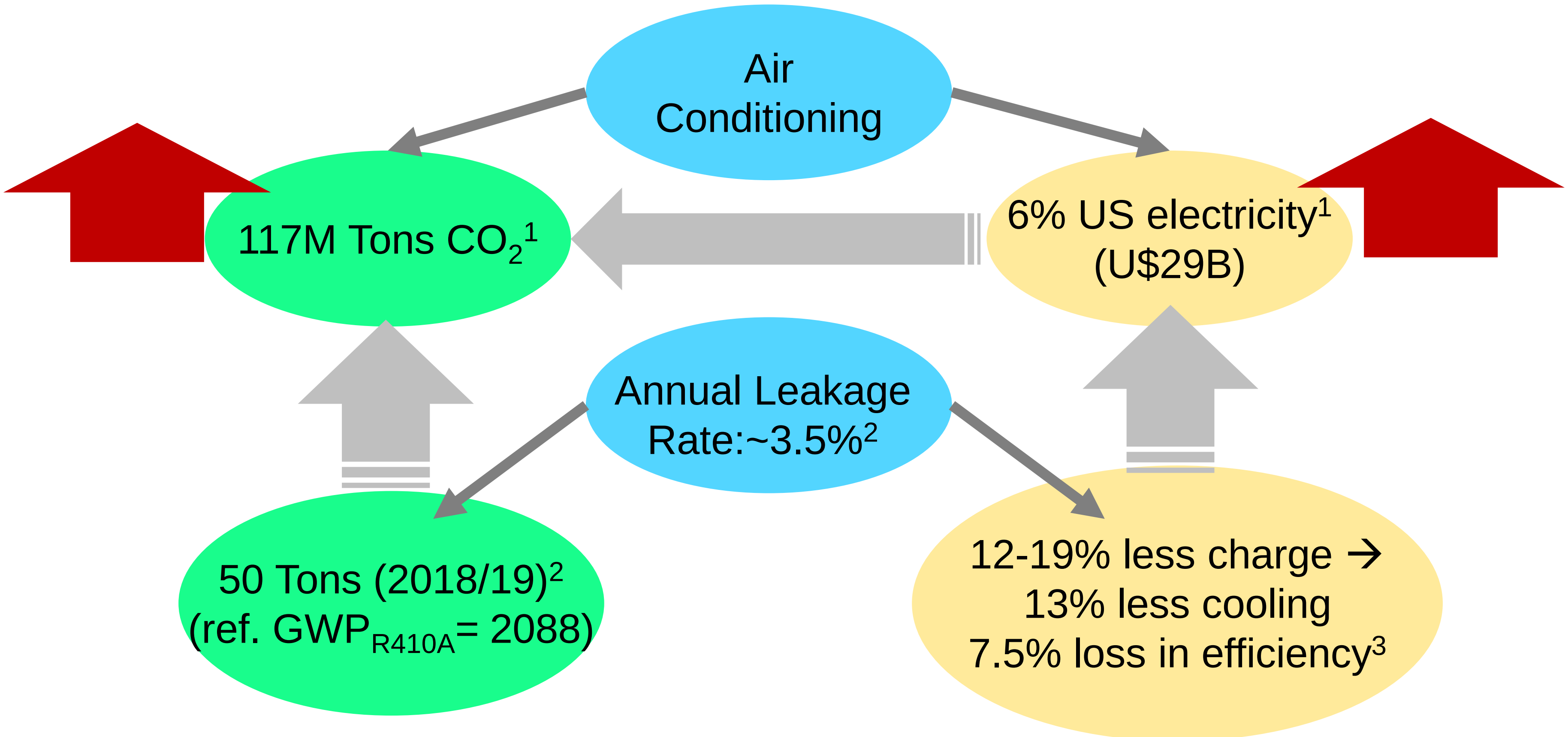
Conceptualize **serpentine heat exchangers** for HVAC application, aiming for **leakage reduction**.

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.

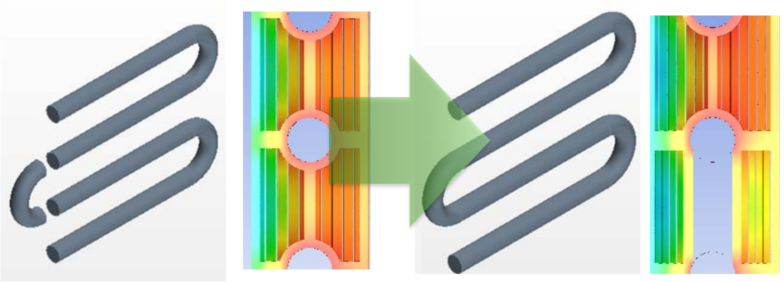
[3] Kim, W. Braun, J.E. Impacts of Refrigerant Charge on Air Conditioner and Heat Pump Performance. International Refrigeration and Air Conditioning Conference at Purdue, July 10-15, 2010

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 HXs**
  - 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

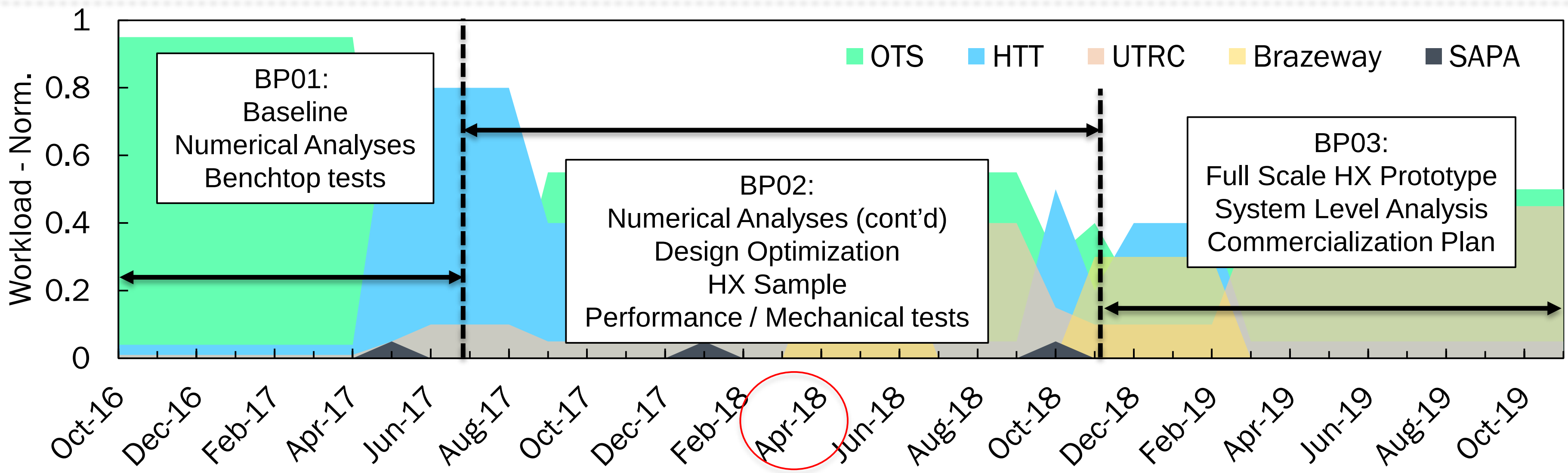
Key Vendors

BRAZEWAY

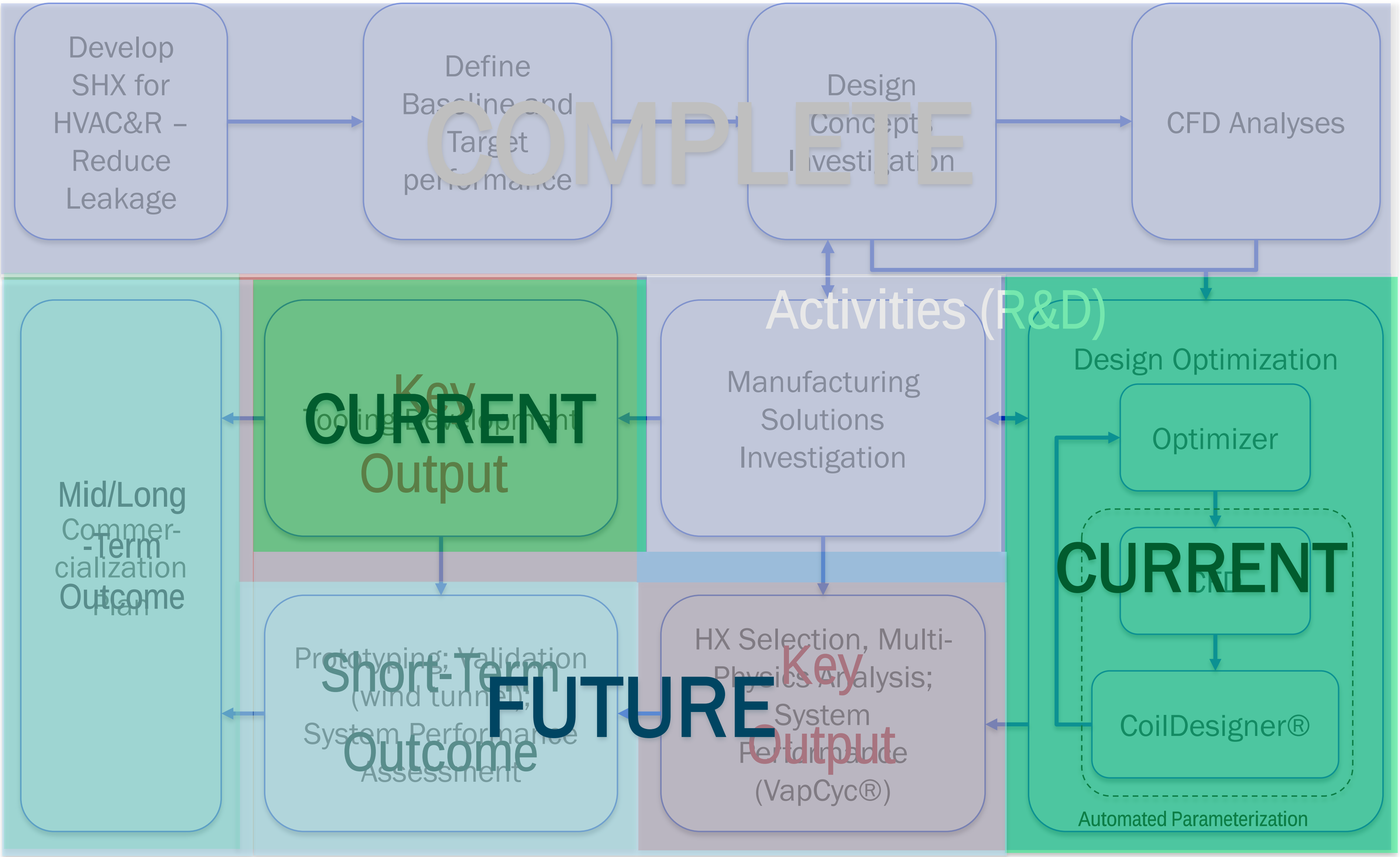
Fin tooling / Serpentines
Fin-tube Assembly

sapa:

Clad aluminum tube supplier

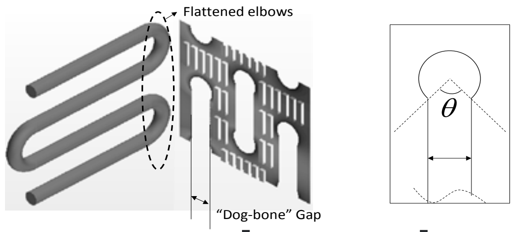


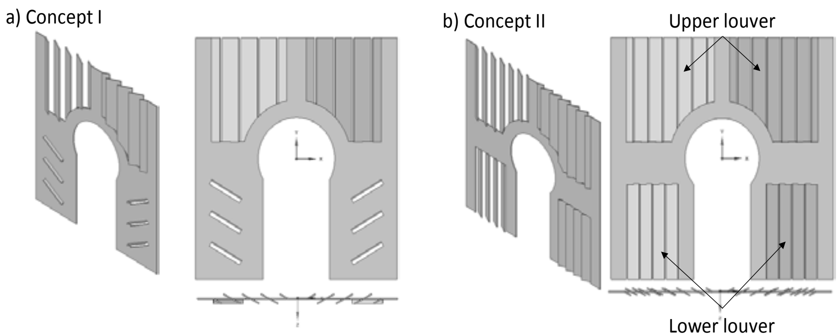
Approach Framework



Design Concepts

- Fin enhancement type: winglets vs. louvers
- Wider fins
- “Dog-bone” cut gap

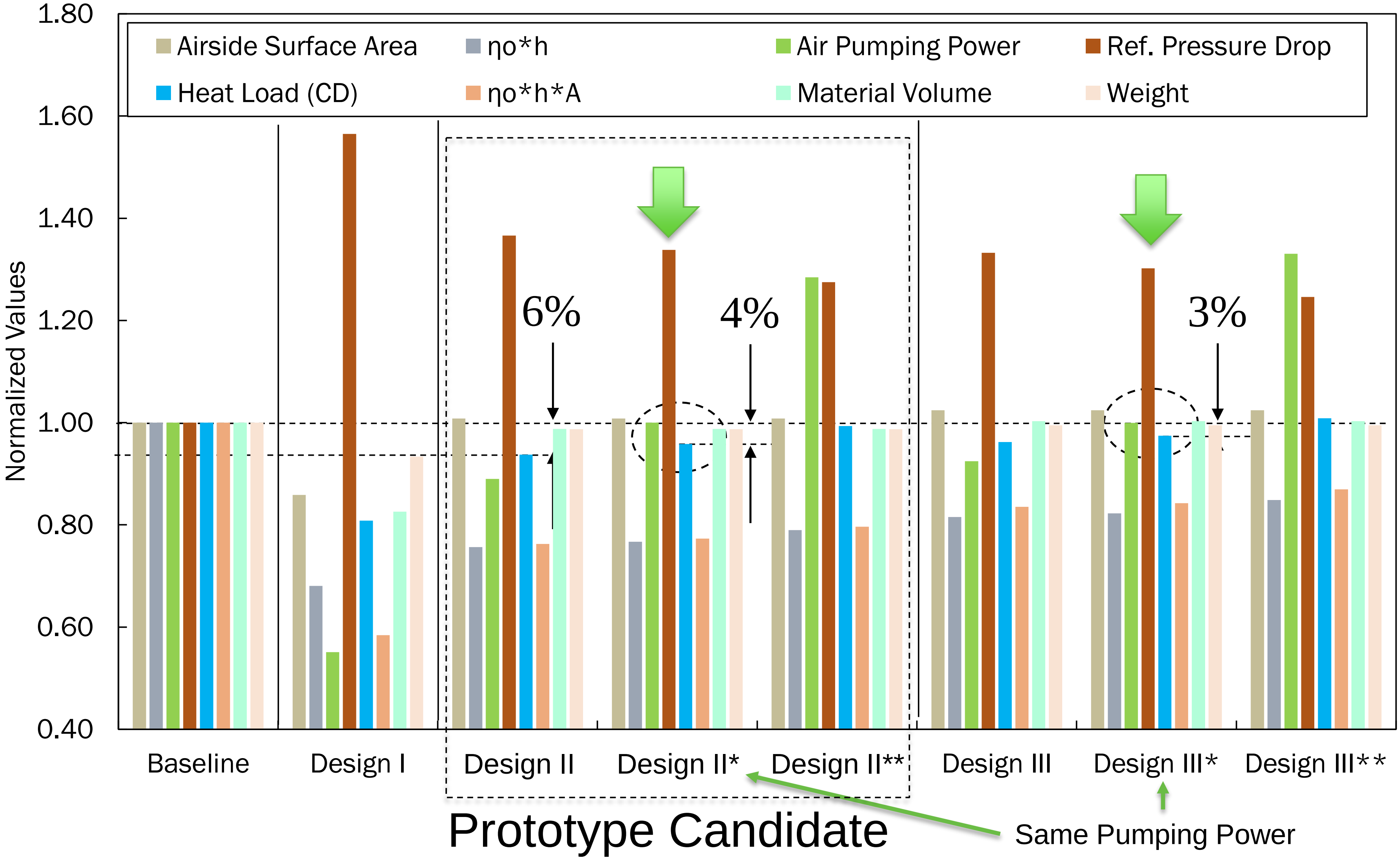




- Parametric study: varying air flow rate

Metric		Baseline	Design I	Design II			Design III		
D_o	m	0.0074	0.0071	0.0071			0.0071		
P_l	m	0.019	0.0187	0.0213			0.0213		
P_t	m	0.0217	0.0207	0.0213			0.0213		
θ	°	N/A	120	120			100		
A_o	m^2	42.44	36.44	42.80			43.49		
u	m/s	1.025	1.025	1.025	1.08	1.2	1.025	1.06	1.2

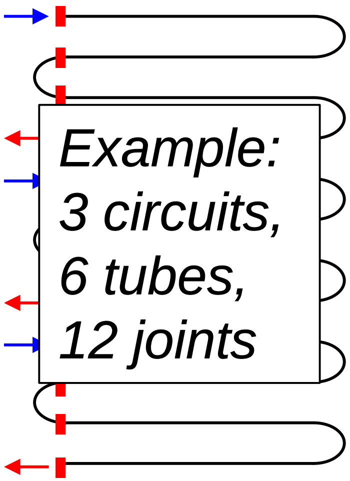
Results

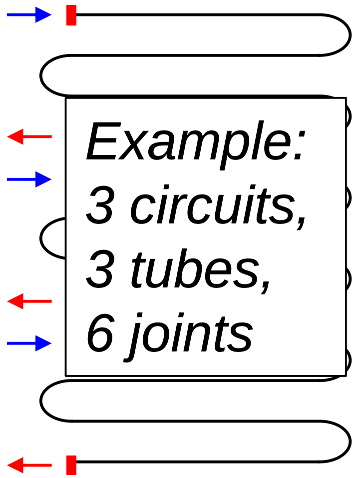


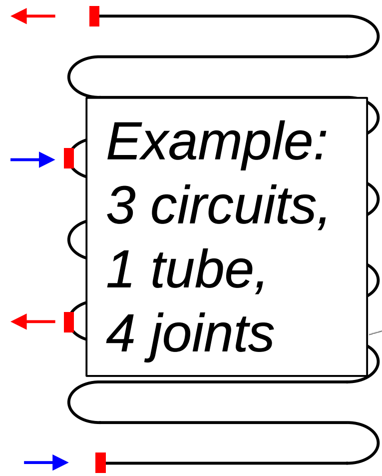
[1]Ref. DP does not account for the penalty in the flattened elbows

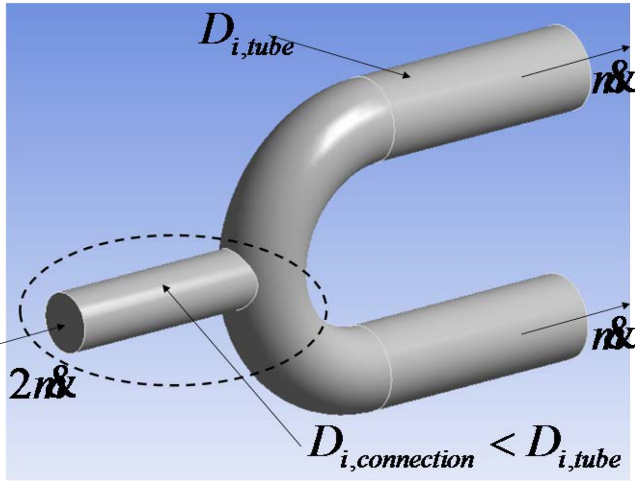
Alternate Circuiting

Conventional Hairpin Circuiting (Baseline)

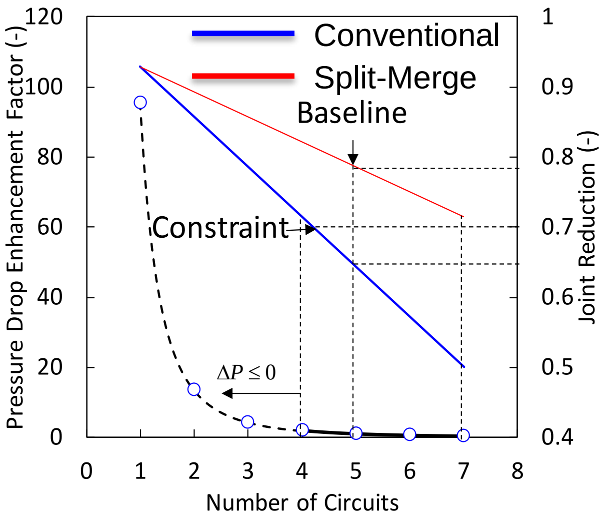








$n_{\text{joints}} = n_{\text{straight\_tube\_section}}$ $n_{\text{joints}} = 2 \cdot n_{\text{circuits}}$ $n_{\text{joints}} = n_{\text{circuits}} + 1$



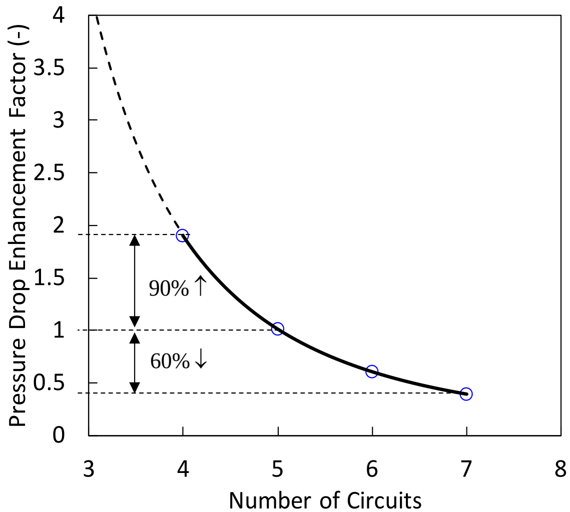


Image curtesy of HTT

Optimization Status

Part I:

Define / Parameterize a Geometry

Build a PPCFD project

Part II:

Define DoE

Run PPCFD

Part III:

Post-Process Data (airside h and ΔP)

Build Metamodel / Correlation

Part IV:

Run AAO

Done

Most time-consuming (engineering)
Coding, debugging, repeatability and reliability testing

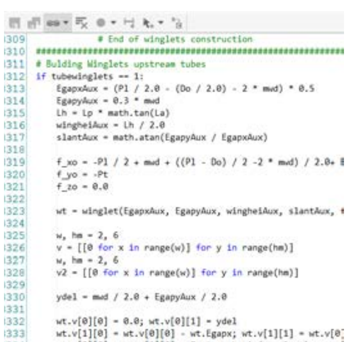
In Progress

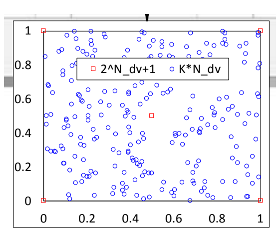
Most computationally intensive

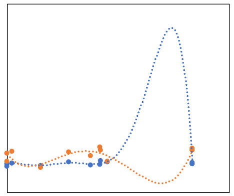
$$N_{DoE} = 2^{N_{dv}} + 1 + K \cdot N_{dv}$$

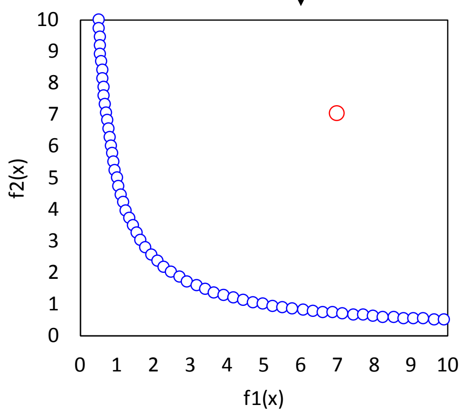
Typically quick and straight-forward

(Additional simulations may be required)



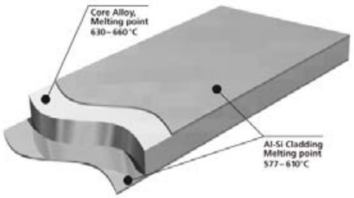






Fin-to-Tube Joining

Approach: clad material on tube surface



Anaerobic vessel

Brazed sample

Image curtesy from HTT (July, 2017)

Durability / robustness tests

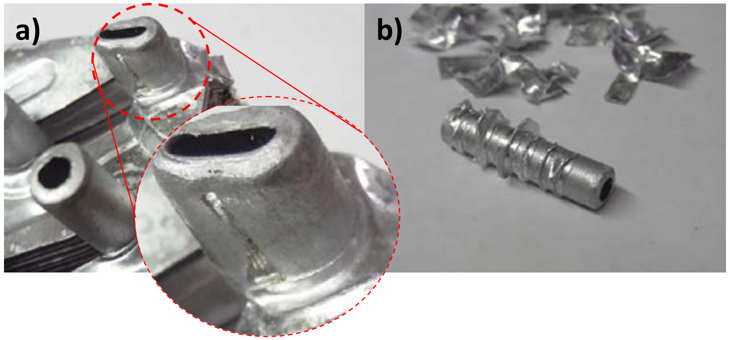


Image curtesy from HTT (July, 2017)

Microsection Analysis:

Conventional “dog-bone” (non-brazed)

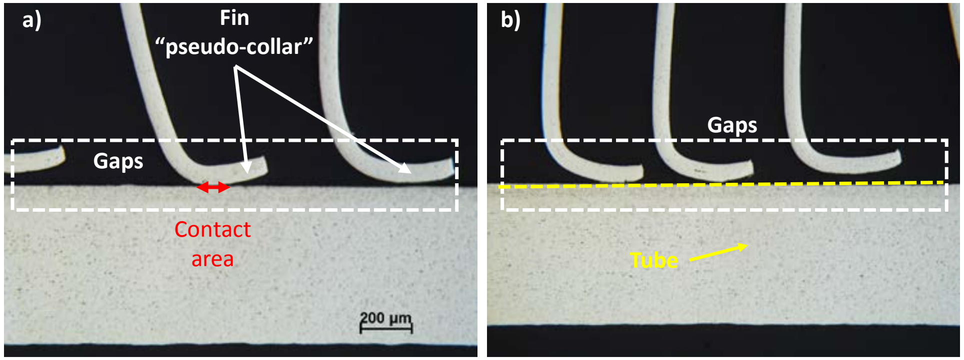


Image curtesy from UTRC (July, 2017)

Brazed “dog-bone”

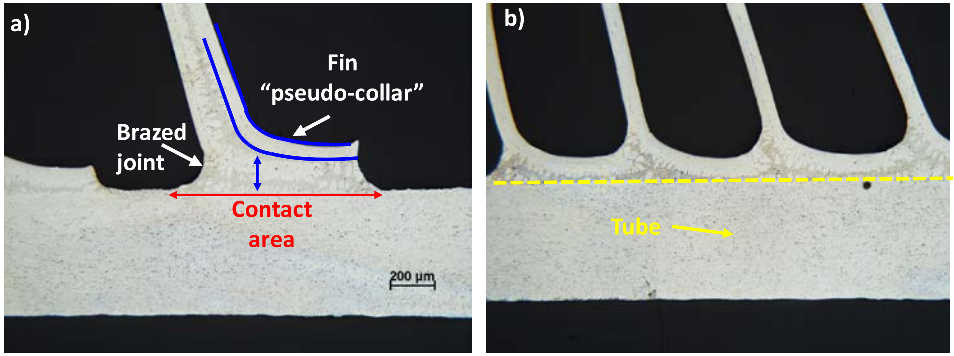


Image curtesy from UTRC (July, 2017)

Split-Merge Connections

Image curtesy from UTRC

Electrical Discharge Machining (EDM)

Image curtesy from UTRC

Image curtesy from UTRC

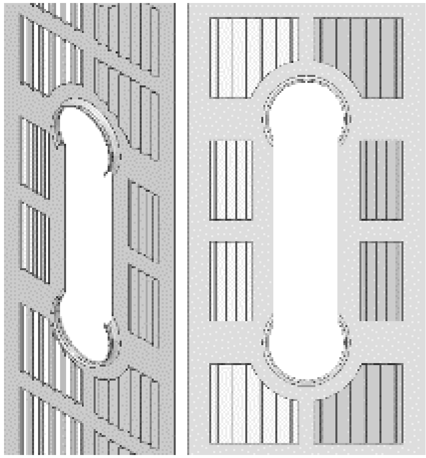
Image curtesy from HTT

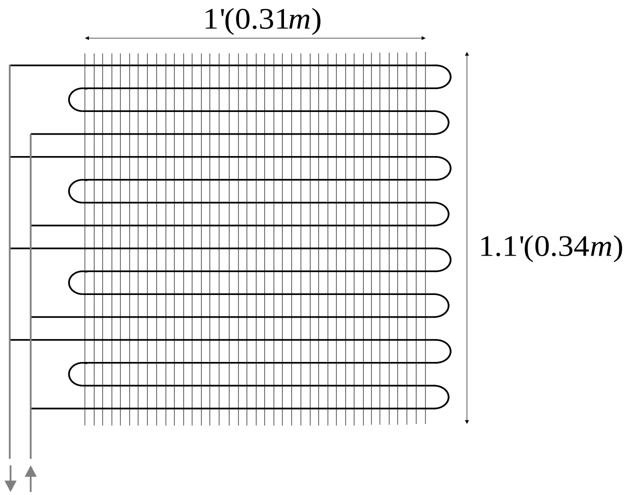
Image curtesy from HTT

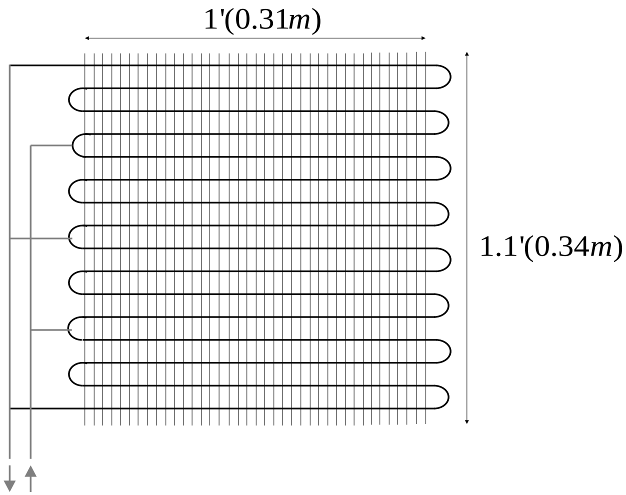
Brazing

Image curtesy from HTT

Concept-to-Proof (Non-Optimum)







Purpose:

- Manufacturing method validation (HTT + Brazeway)
- Air-to-water testing (OTS wind-tunnel) → CFD model validation

Temporary Split/Merge Joints

Conclusions and Future Work

- **Successful numerical demonstration of competitive performance (< 5% of capacity)**
- **Promising solutions to address main challenges:**
  – Fin surface area → wider fins
  – Contact resistance → brazing (~0.0, i.e. no visible gaps)
  – Ref. pressure drop vs. joint reduction → split-merge circuiting
- **Successful demonstration of manufacturing solutions**
- **Next steps**
  – 1'x1' HX sample → manufacturing and model validation
  – Finalize optimization / select final concept for large HX sample

Thank You

Optimized Thermal Systems, Inc.
Dr. Daniel Bacellar
bacellar@optimizedthermalsystems.com

Project Budget

- BP1 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					
	10/2016 – 08/2017		08/2017 – 11/2018		11/2018 – 10/2019	
	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	$73,300	$17,891	-	-

Project Plan and Schedule

Project Schedule												
Project Start: 10/2016		Completed Work										
Projected End: 10/2019		Active Task (in progress work)										
		Milestone/Deliverable (Originally Planned)										
		Milestone/Deliverable (Actual)										
	FY2017				FY2018				FY2019			
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												
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												
Current/Future Work												
3.2 Develop Optimized Fin Geometry												
4.1 Design Fin Tooling												
4.2 Construct Prototype Heat Exchangers												
5.1 Heat Exchanger Performance Testing												
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												