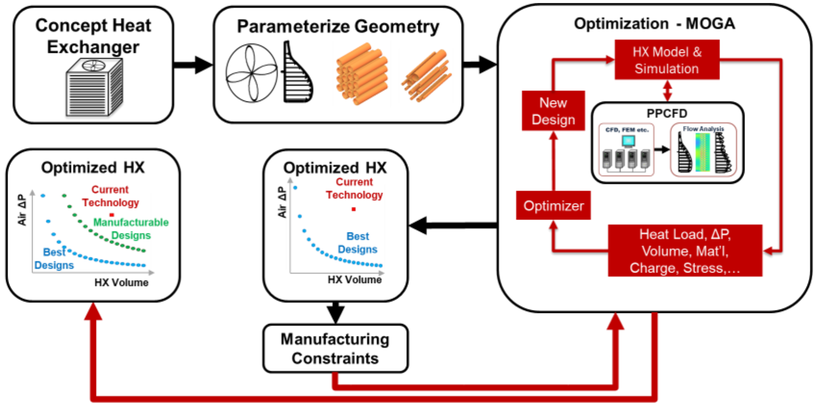
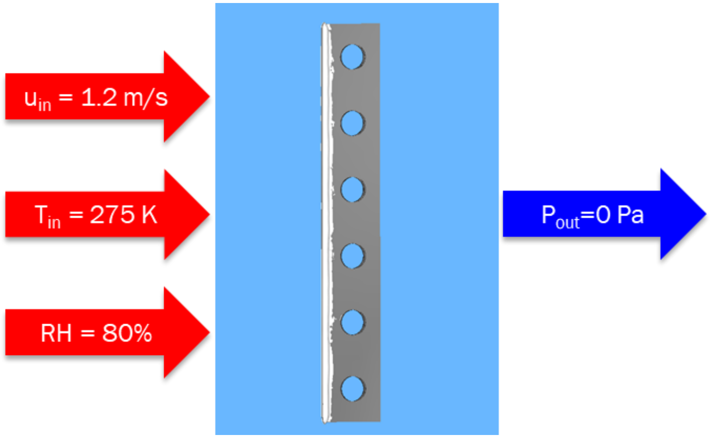
Hybrid Manufacturing for High Performance Air-to-Refrigerant Heat Exchangers



PPCFD = Parallel Parameterized Computational Fluid Dynamics | MOGA = Multi-Objective Genetic Algorithm

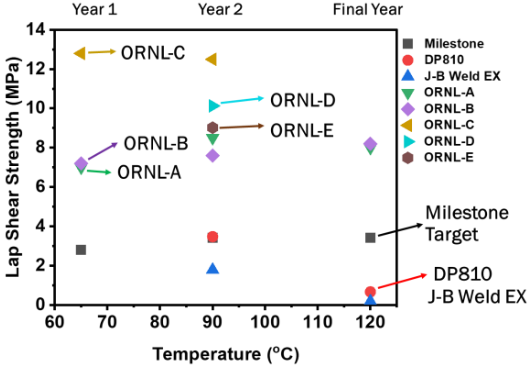


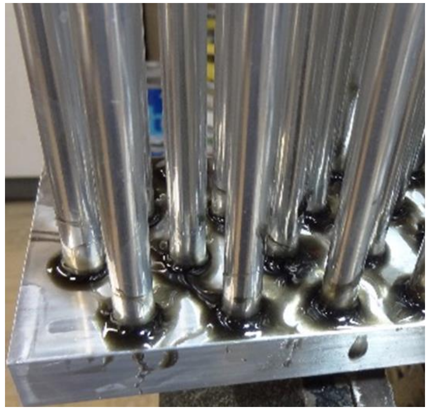
u_{in} = 1.2 m/s

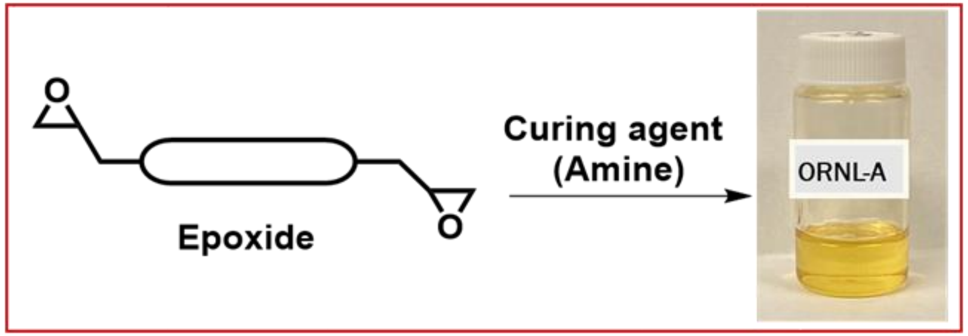
T_{in} = 275 K

RH = 80%

P_{out}=0 Pa







Performing Organizations: University of Maryland, Heat Transfer Technologies, LLC., Oak Ridge National Laboratory

Prof. Reinhard Radermacher, *Dr. Vikrant Aute*

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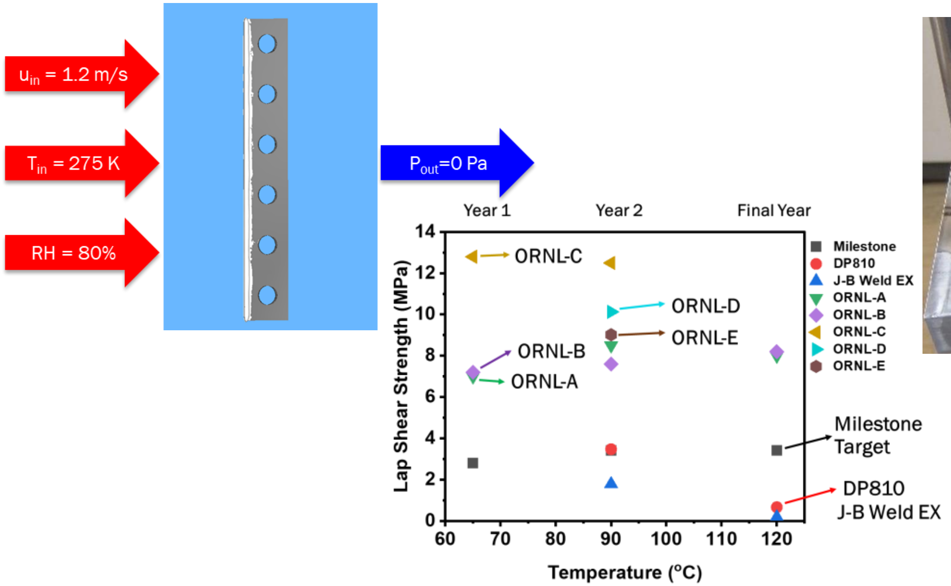
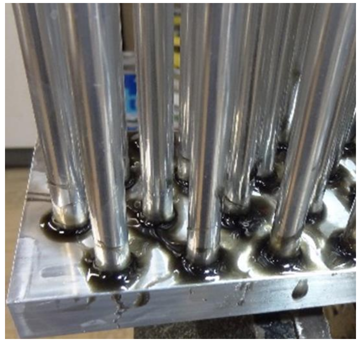
DE-EE0009677

Project Summary

Objective and outcome

- Develop adhesive-based hybrid manufacturing method for air-to-refrigerant HXs which is >50% cheaper & >36% less energy in manufacturing
- Develop novel air-to-refrigerant variable geometry HXs with higher compactness, improved frosting / maldistribution resilience, & less refrigerant
- Framework validation through laboratory-scale & field-scale experimental testing





Team and Partners

University of Maryland 1856
CENTER FOR ENVIRONMENTAL ENERGY ENGINEERING

Heat Transfer Technologies

OAK RIDGE National Laboratory

Stats

Performance Period: Oct. 2021 – Sept. 2024

DOE budget: $1400K, Cost Share: $350K

Milestone 1: 1st adhesive; HX design framework + proof-of-concept prototypes

Milestone 2: 2nd adhesive; Lab-scale HXs + testing

Milestone 3: Final adhesive; Field-scale HXs + testing

Problem

- **Heat eXchangers (HX) are key components in HVAC&R systems**
  - Hold refrigerant charge; impact system efficiency
- **Improved HXs can lead to**
  - Less refrigerant charge
  - Less material use, size/weight reduction
  - Lower energy consumption, emissions, & costs
- **Challenges in bringing new HX technology to market**
  - Novel designs must be at least 20% better
  - Lack of basic heat transfer & flow fundamentals, correlations
  - Component availability
  - Joining/manufacturing techniques
  - Flow maldistribution
  - Frost accumulation

Alignment

- **Develop an adhesive based hybrid manufacturing method for air-to-refrigerant HXs**
  - ≥50% cheaper
  - ≥36% less energy in manufacturing
  - More reliable than existing solder-based methods
- **Develop novel air-to-refrigerant variable geometry heat exchangers (VGHX)**
  - Contain less refrigerant
  - Are more compact
  - Are more resilient to frost growth & refrigerant maldistribution
- **Conduct frost accumulation & reliability tests**
  - Reduce refrigerant maldistribution from frost growth
- **Delivery of HX prototypes to industrial partners for independent performance testing**

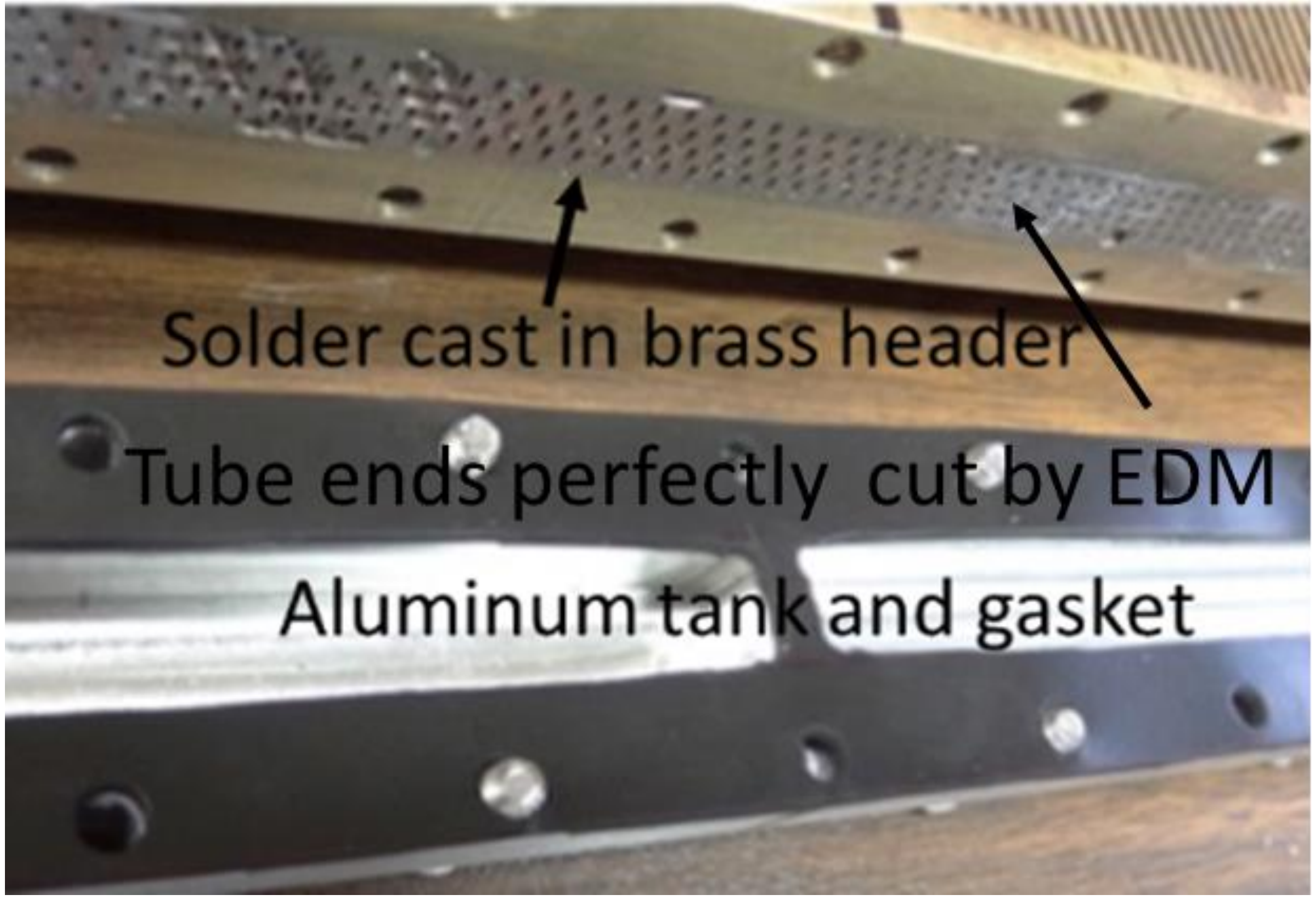
Impact & Target Market

- **Impact**
  - New manufacturing method expected to be 50% cheaper & consume 36% less energy than existing solder-based methods
    - Adhesive-based approach has potential to reduce production barriers for next generation HXs
    - Improved reliability over solder-based methods to reduce refrigerant leakage (1.5-2.0% of total emissions)
  - Novel HX designs with improved resilience to field challenges
    - ≥10% longer operation time under frost accumulation conditions
    - ≥20% improvement in uniformity of evaporator mass flow rate
  - HX design framework and technical guidelines for adhesive-based hybrid manufacturing thereof
    - Modular technology with multiple product levels, e.g., fully variable geometry HXs (premium) vs. small-diameter round tubes with rectangular headers (affordable)
  - Industry involvement in HX design development & testing with immediate and iterative feedback on commercial viability and tech-to-market

- **Target Market**
  - Residential and commercial air conditioners and heat pumps
  - New construction and retrofit applications

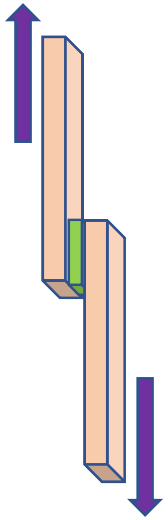
Approach: HX Manufacturing – State-of-the-Art

- **Cast based method**
  - High energy consumption to cast metals
  - Requires corrosive fluxes to clean metals
  - Costly EDM cutting of tube ends
  - Requires tanks and gasket seals

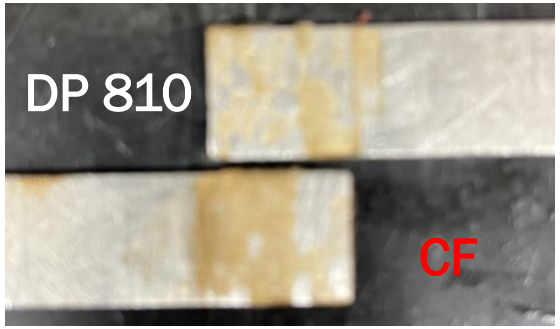


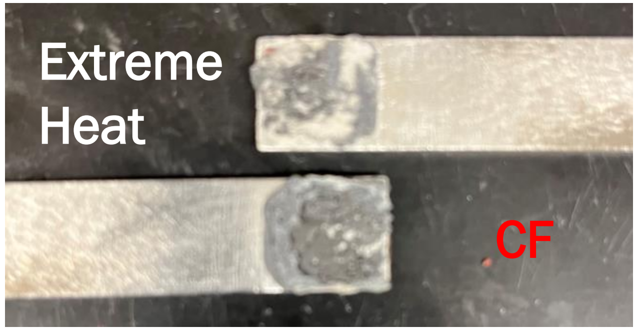
Approach: State-of-the-Art Commercial Adhesives

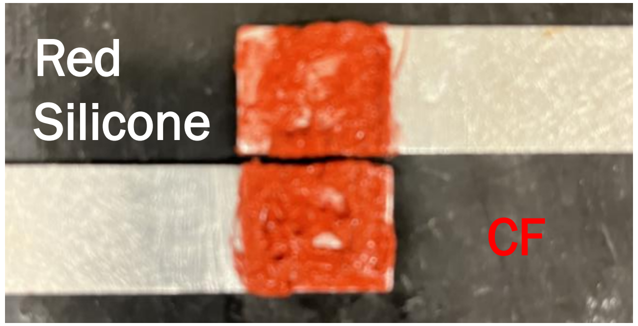
Commercial adhesives	Tested substrate	Temperature (°C)	Lap shear strength (MPa)
3M DP 810 (Acrylate)	Aluminum	90	3.47
J-B Weld Extreme Heat (Epoxy)	Aluminum	90	1.78
J-B Weld Hi-temp RTV (Silicone)	Aluminum	90	0.34



Lap Shear Test





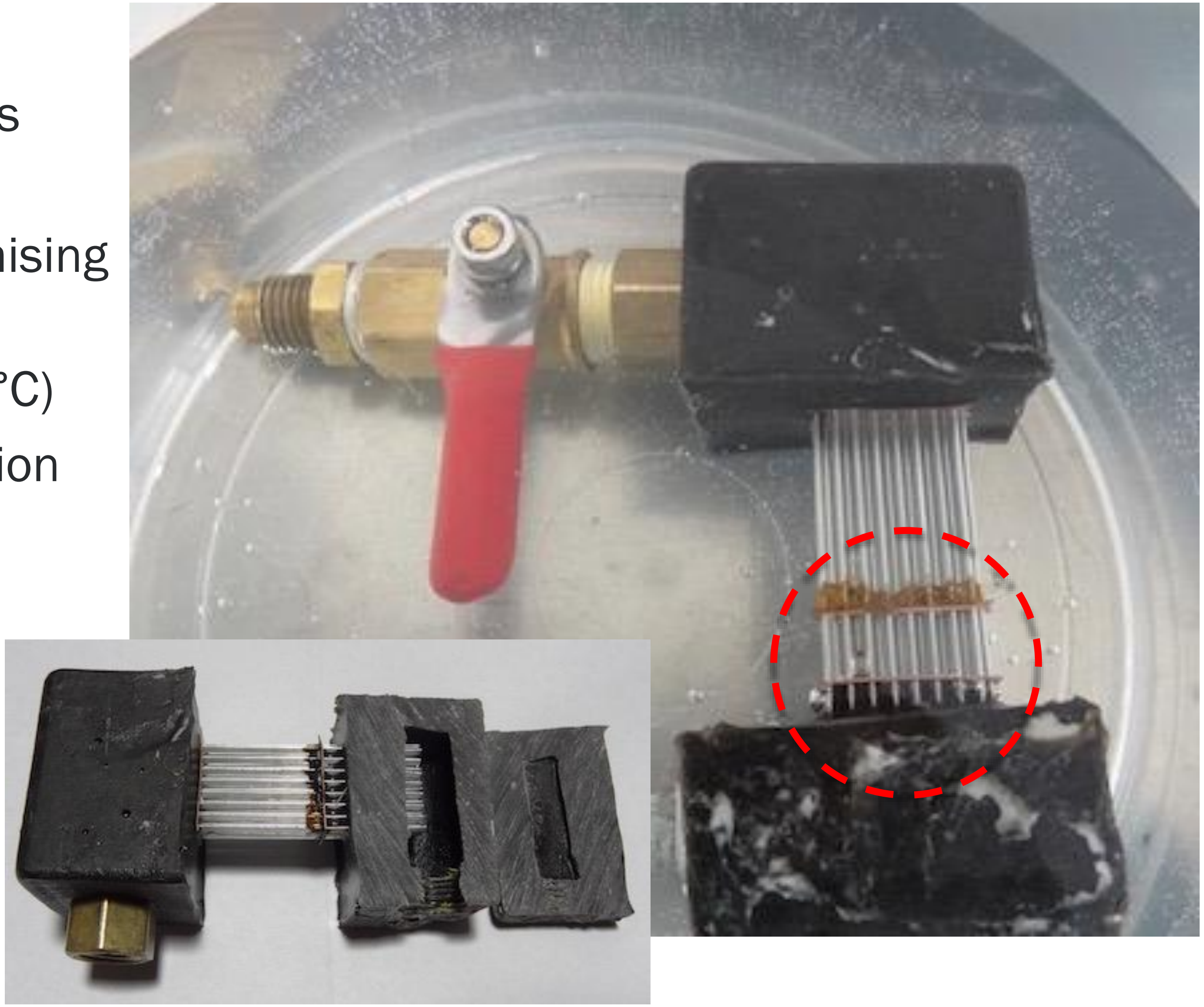


Cohesive Failure (CF): Failure occurs within adhesive which indicates weak adhesion

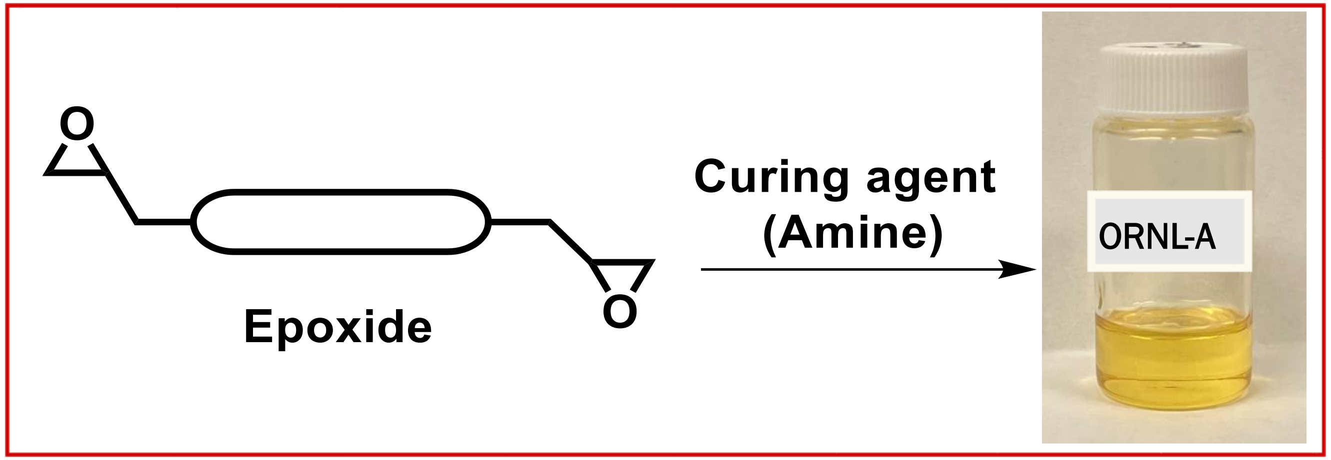
Approach: Initial Fabrication

- **Commercially available adhesives**
  - Previous work evaluated 23 options
    - Most had tube-adhesive leaks
  - Acrylic-Based DP810 → most promising
  - Withstood 2.8 MPa at room temperature (Max temperature 50°C)
  - Medium viscosity → hard penetration

- **Epoxy-based adhesives**
  - Excellent lap shear
  - Low viscosity → easy penetration
  - High-temp capable (>90°C)



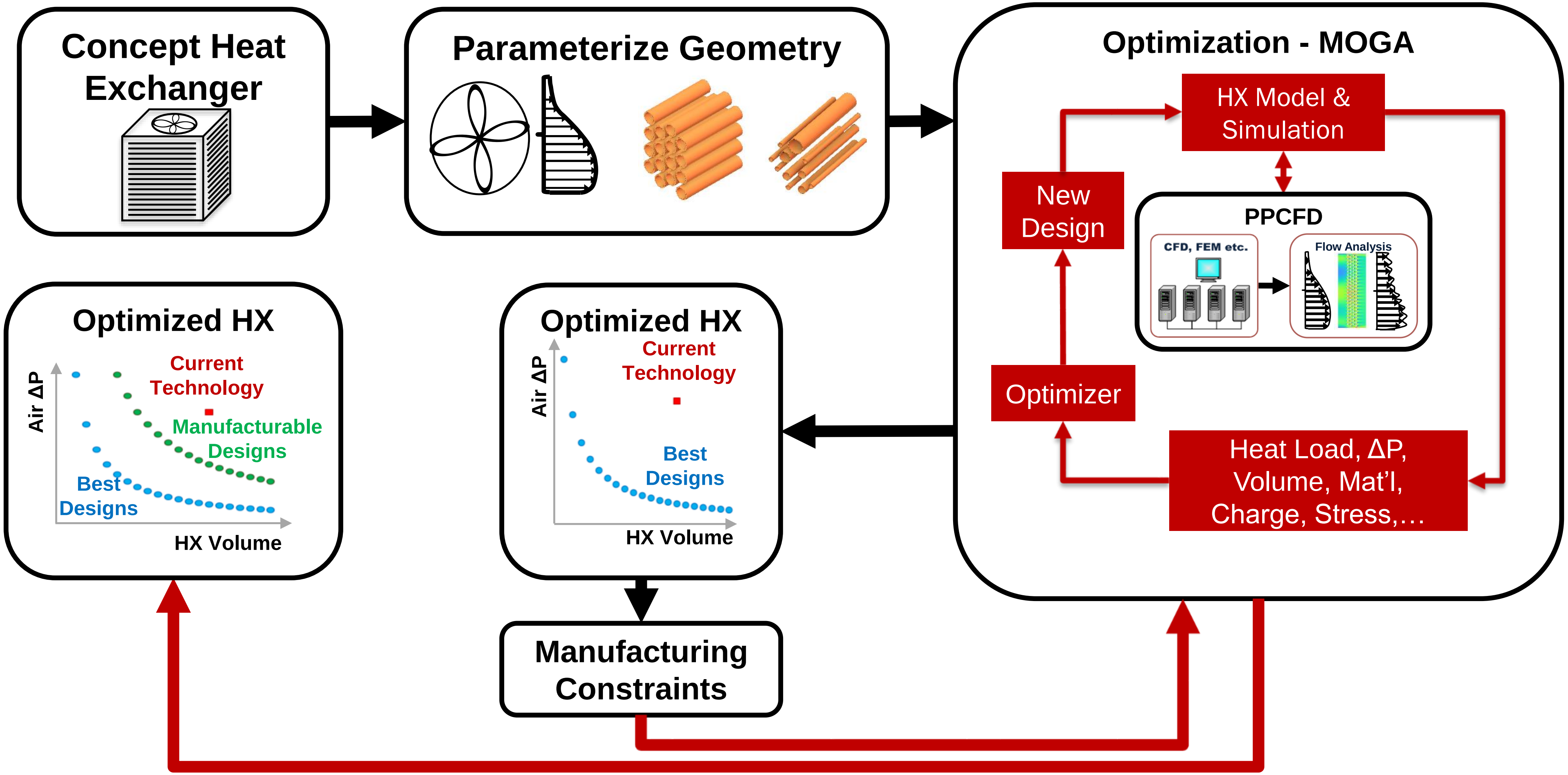
Approach: Design of High Temperature Adhesives



Failure Mode

Adhesives	Lap Shear Adhesion (MPa) at 65^{o}C	Lap Shear Adhesion (MPa) at 90^{o}C	Failure Mode
ORNL-A	7	8.5	Adhesive failure
ORNL-B	7.2	7.6	Adhesive failure
ORNL-C	12.8	12.5	Adhesive failure
ORNL-D	N/A	10.13	Adhesive failure
ORNL-E	N/A	9.02	Adhesive failure

Approach: Design & Optimization Framework



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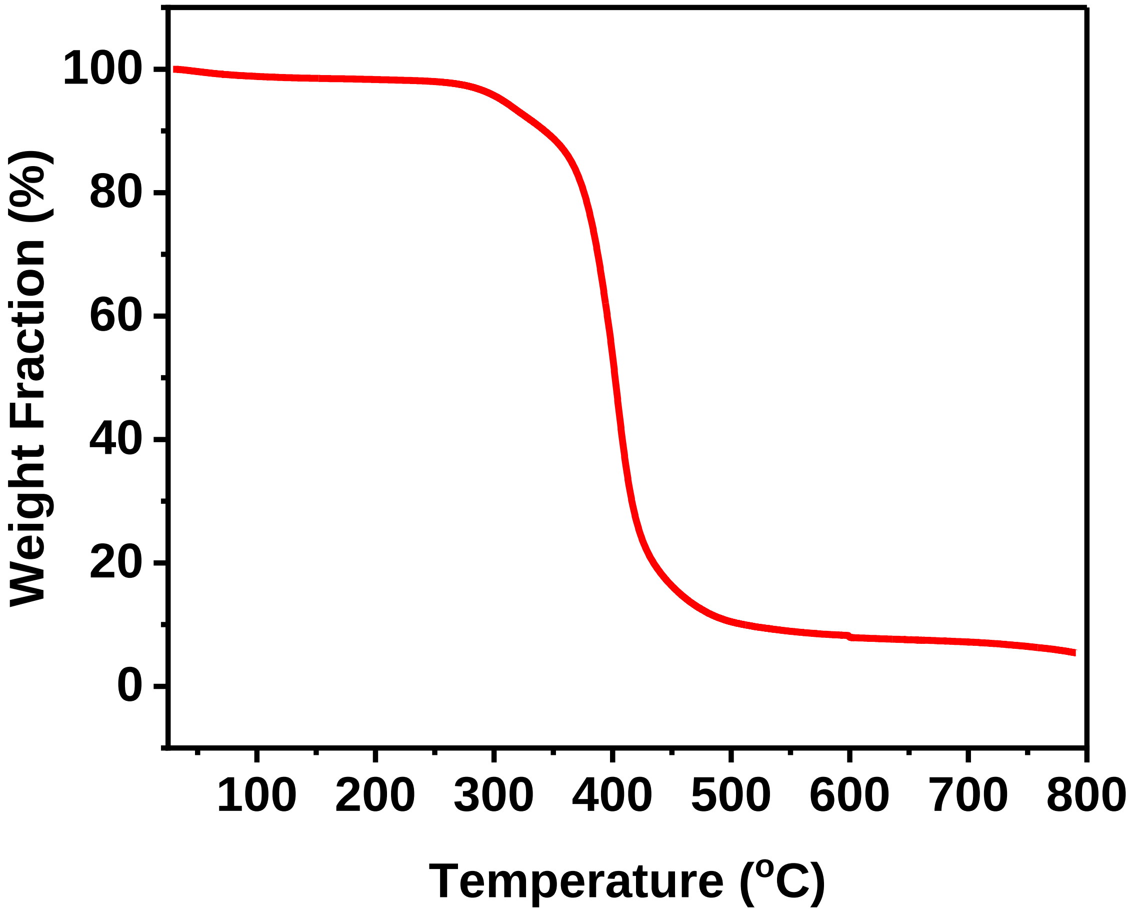
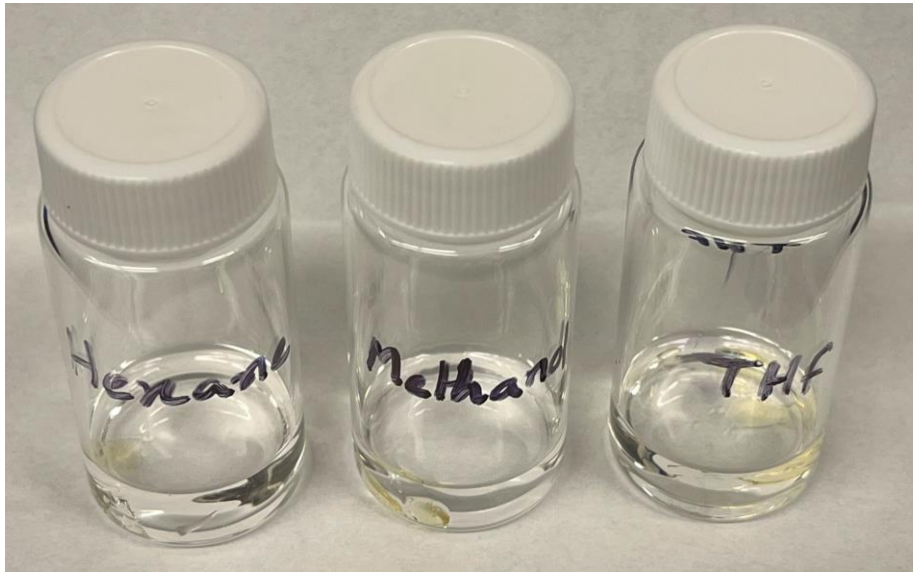
Progress: Adhesive Temperature Stability & Solvent Resistance

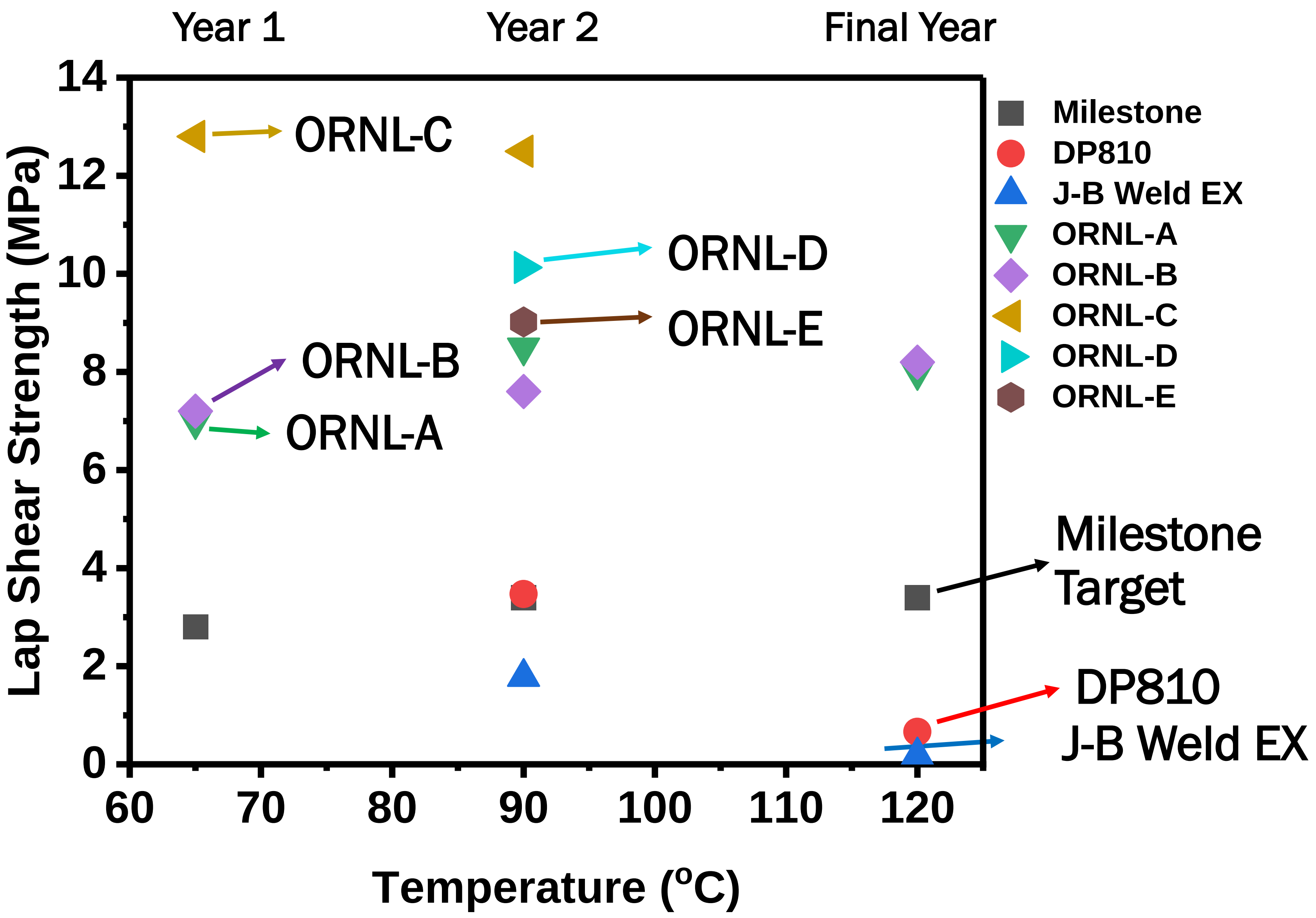
TGA plot indicates very good thermal stability of our adhesive



Excellent solvent resistance

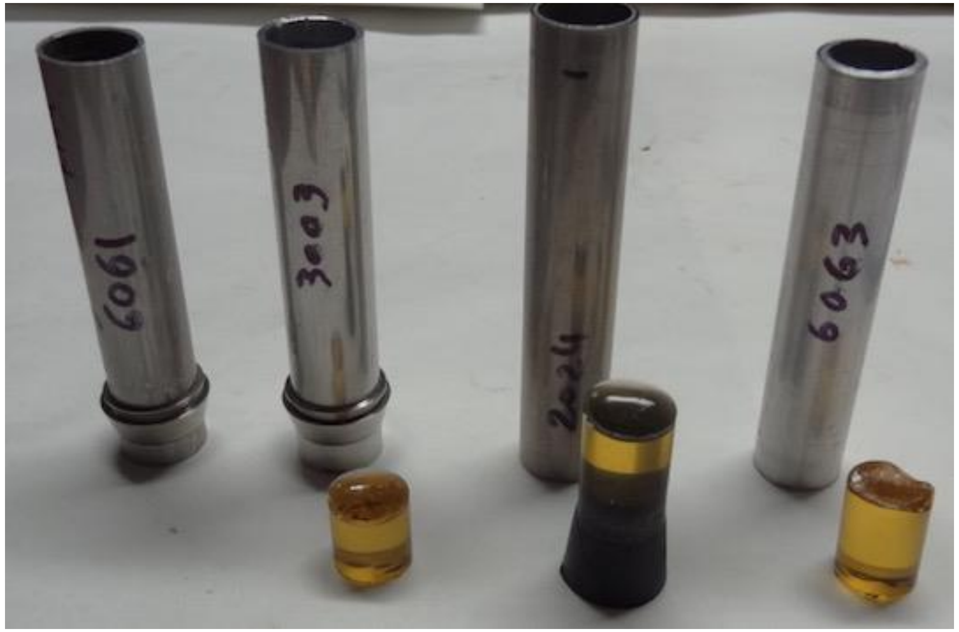


Progress: Current Adhesive Development



Progress: Tube-Adhesive Pressure Testing

- DP8407NS held 3 MPa at 60°C for 30+ minutes (M2.4)
- ORNL-A epoxy held 3.4 MPa at 90°C for 30+ minutes (M3.2) in a 3/8” OD tube
- Narrow bonding area improves adhesion performance



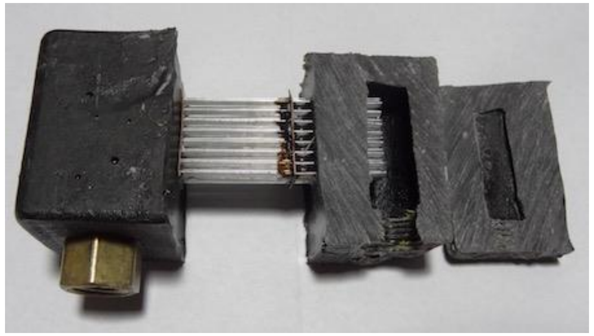
Aluminum Alloy Testing

ORNL-A Test

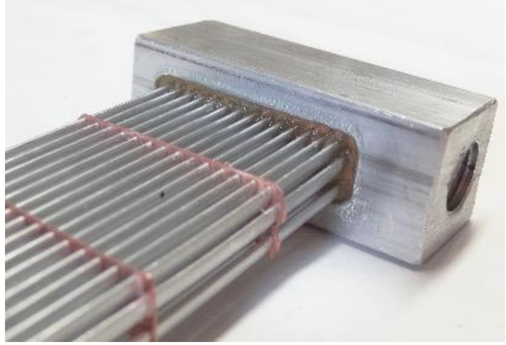
DP8407NS Test

Progress: Heat Exchanger Fabrication

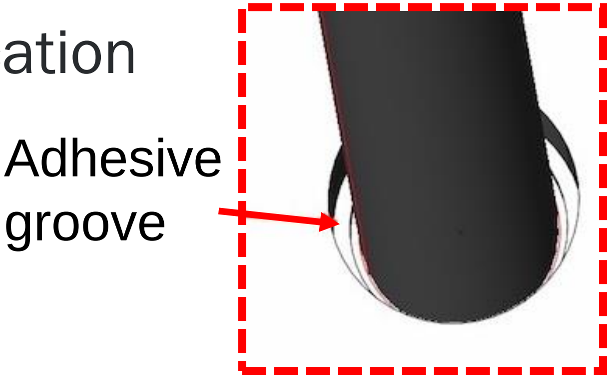
- **Initial Approach**
  - – All adhesive header

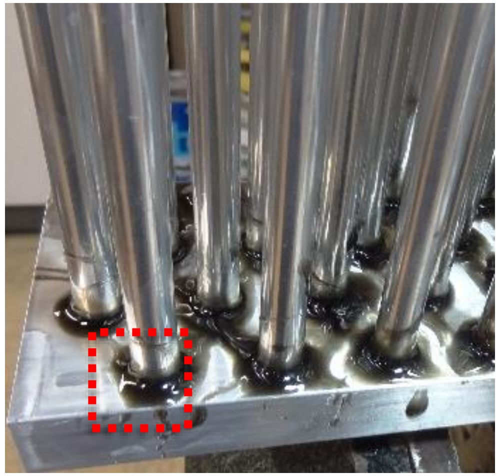


- **Manifold Method**
  - – Reduced cost and adhesive consumption
  - – Poor adhesive penetration → leakage



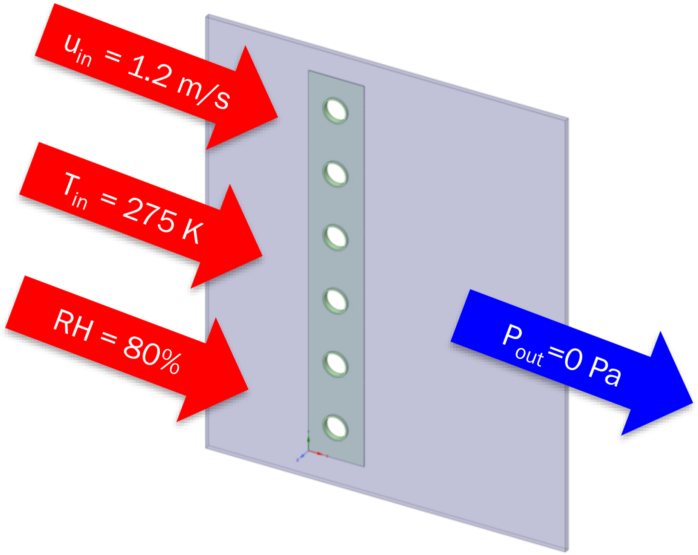
- **Block Header Design**
  - – 1.5 mm groove for adhesive application

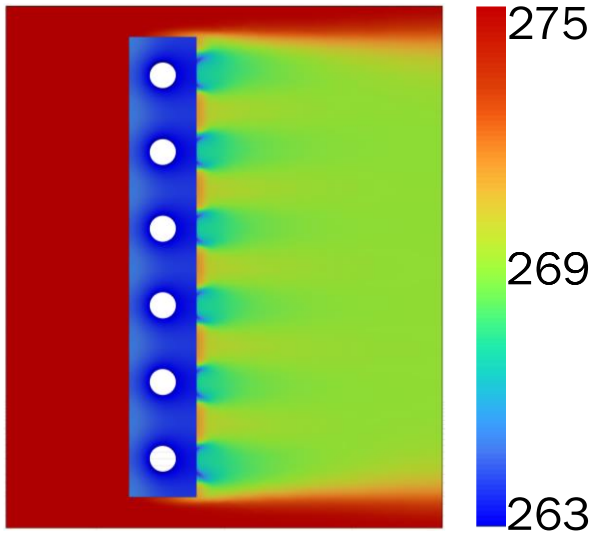


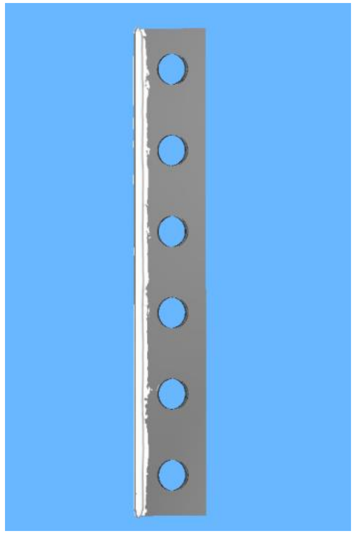


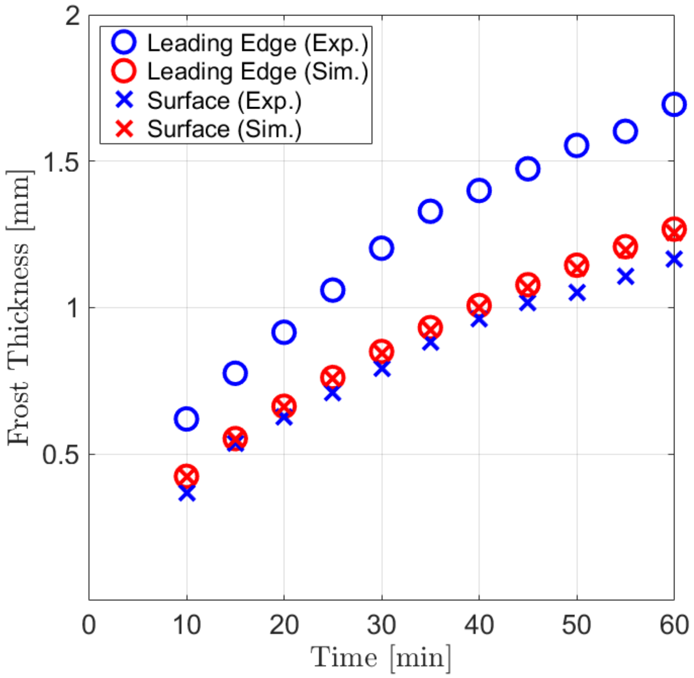
Progress: Frost Accumulation Modeling

- **Multiphysics frost accumulation simulations validated with literature data**
- **Model development challenges**
  - Fin conduction (ice accretion model cannot simulate fin conduction)
  - Ice/frost thermophysical properties cause solver stability issues









Assumptions

Constant ice density

Frosting period: 3600s

Settings

Mesh: ~800,000 elements

dt = 0.1s

Future Work

- **Design and Analysis**
  - Finalize frost accumulation analysis
  - Increase scope of packaging considerations in flow prediction
  - VGHX design with improved frost resilience (>10% operational time)
- **Fabrication**
  - Testing and evaluation of block header design
  - Develop additional manufacturing methods
  - HX prototyping (~3 kW lab-scale & ~5-10 kW field-scale)
- **Testing**
  - Continued adhesive testing with tube-pressure test rig
  - Proof-of-concept HX testing & validation
    - Lab-scale: in-house & industry partners
    - Field-scale: industry partners

Thank You

Performing Organizations: University of Maryland, Heat Transfer Technologies, LLC., Oak Ridge National Laboratory
Prof. Reinhard Radermacher, *Dr. Vikrant Aute*
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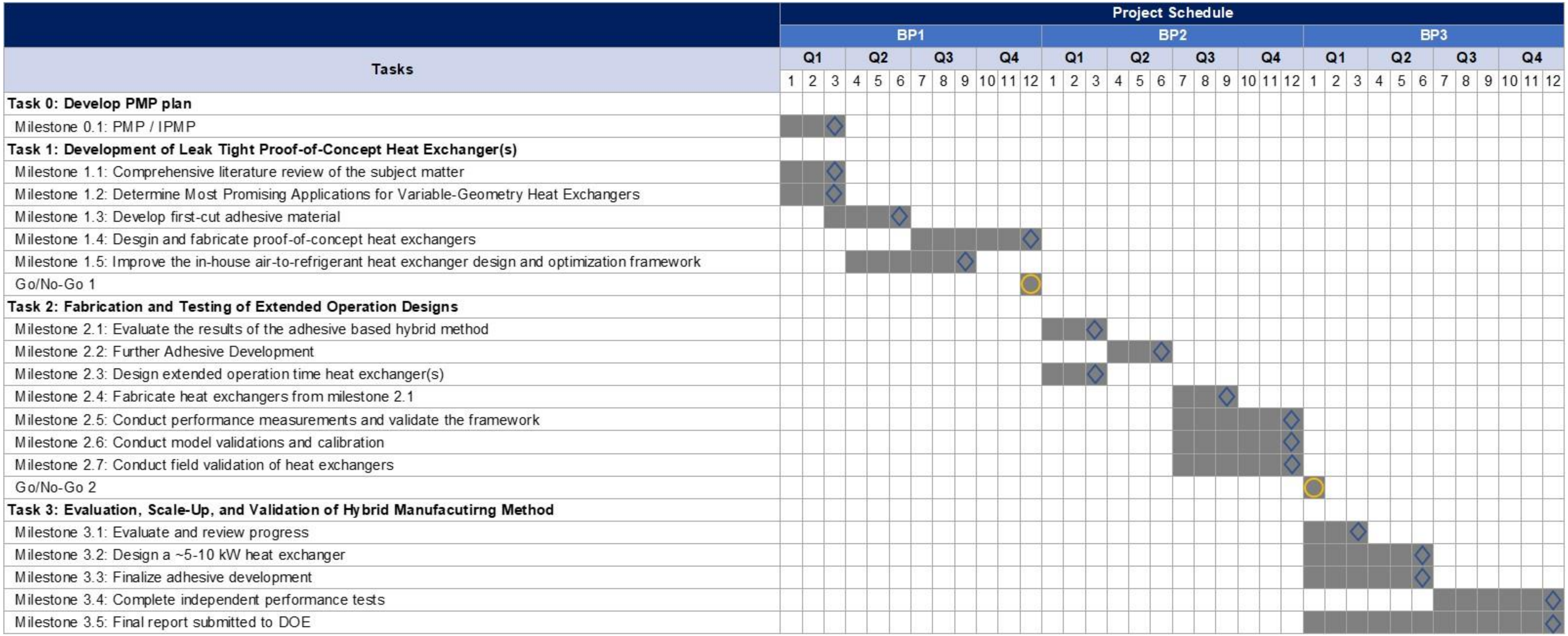
REFERENCE SLIDES

Project Execution



Tasks	Project Schedule																																			
	BP1												BP2												BP3											
	Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4		
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Task 0: Develop PMP plan																																				
Milestone 0.1: PMP / IPMP	▨	▨	◇																																	
Task 1: Development of Leak Tight Proof-of-Concept Heat Exchanger(s)																																				
Milestone 1.1: Comprehensive literature review of the subject matter	▨	▨	◇																																	
Milestone 1.2: Determine Most Promising Applications for Variable-Geometry Heat Exchangers	▨	▨	◇																																	
Milestone 1.3: Develop first-cut adhesive material			▨	▨	▨	◇																														
Milestone 1.4: Desgin and fabricate proof-of-concept heat exchangers							▨	▨	▨	▨	▨	◇																								
Milestone 1.5: Improve the in-house air-to-refrigerant heat exchanger design and optimization framework				▨	▨	▨	▨	▨	◇																											
Go/No-Go 1												○																								
Task 2: Fabrication and Testing of Extended Operation Designs																																				
Milestone 2.1: Evaluate the results of the adhesive based hybrid method													▨	▨	◇																					
Milestone 2.2: Further Adhesive Development																▨	▨	◇																		
Milestone 2.3: Design extended operation time heat exchanger(s)													▨	▨	◇																					
Milestone 2.4: Fabricate heat exchangers from milestone 2.1																			▨	▨	◇															
Milestone 2.5: Conduct performance measurements and validate the framework																			▨	▨	▨	▨	▨	◇												
Milestone 2.6: Conduct model validations and calibration																			▨	▨	▨	▨	▨	◇												
Milestone 2.7: Conduct field validation of heat exchangers																			▨	▨	▨	▨	▨	◇												
Go/No-Go 2																									○											
Task 3: Evaluation, Scale-Up, and Validation of Hybrid Manufacutirng Method																																				
Milestone 3.1: Evaluate and review progress																									▨	▨	◇									
Milestone 3.2: Design a ~5-10 kW heat exchanger																									▨	▨	▨	▨	▨	◇						
Milestone 3.3: Finalize adhesive development																									▨	▨	▨	▨	▨	◇						
Milestone 3.4: Complete independent performance tests																															▨	▨	▨	▨	▨	◇
Milestone 3.5: Final report submitted to DOE																									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	◇

◇ Milestone ○ Go/No-Go

Team

- **University of Maryland (Prime recipient)**
  - Component modeling/design, data analysis, project management
- **Heat Transfer Technologies, LLC (Sub-recipient)**
  - Heat exchanger design, assembly, technical advisor
- **Oak Ridge National Laboratory (Sub-recipient)**
  - Adhesive development, laboratory testing, technical advisor
- **Industry Partners**
  - 3M
  - Carrier
  - Goodman / Daikin Comfort Technologies
  - Honeywell
  - Small Tube Products