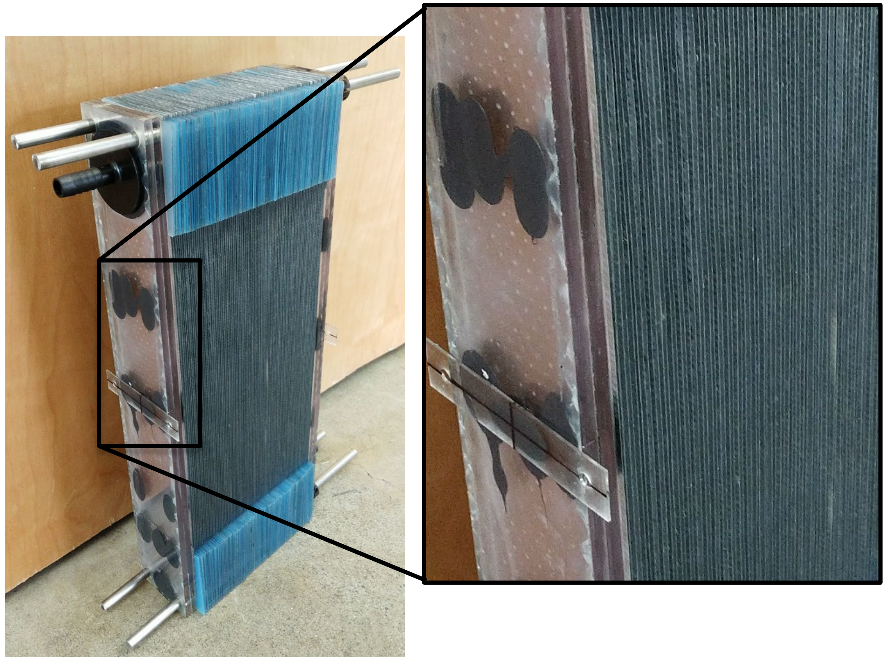
High-Performance Membrane Heat Exchangers for HVAC



Treau, Inc. DBA Gradient
Dr. Jason Wexler
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Project Summary

Timeline:

Start date: 05/2019

Planned end date: 05/2021 (05/2022)

Key Milestones

1. Fabrication of multilayer polymer pouch (01/2020)
2. Multilayer polymer HX prototype (09/2020)
3. Experiment/model agreement (07/2021)

Budget:

Total Project $ to Date:

- DOE: $317,850
- Cost Share: $0

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- DOE: $ 999,999
- Cost Share: $0

Key Partners:

GRADIENT

Otherlab

Project Outcome:

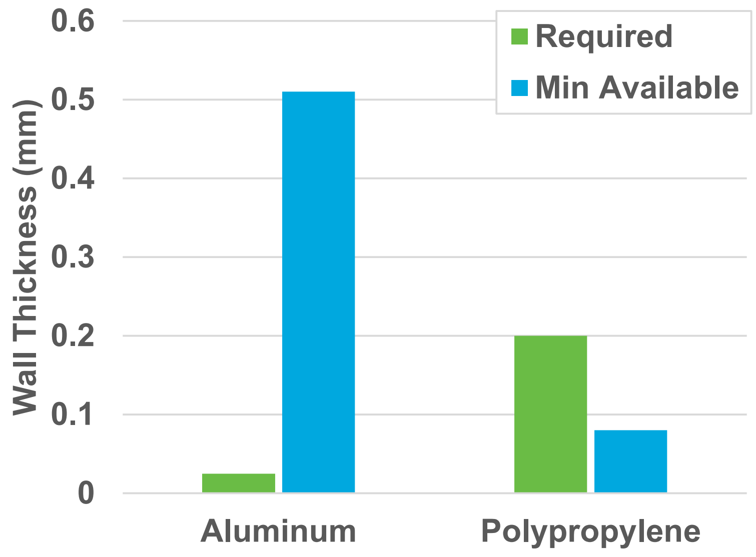
Establish **rapid, low-cost manufacturing methods** for thin-film polymer heat exchangers

Design thin-film polymer heat exchangers that show **cost and performance improvements** relative to the state-of-the-art

Long-term: integration with high-performing HVAC system

Challenge

- Liquid-air heat exchangers constructed from metal use more material than required for the pressures they must sustain, resulting in high costs
- Polymer heat exchangers can have smaller wall thicknesses, resulting in less overall material
- Additional advantages of polymers
  - Improved corrosion resistance
  - Low material cost
- Low-cost liquid-air heat exchangers can enable economical indirect-coupled HVAC systems
  - Increases potential for use of higher performing refrigerants with toxicity or flammability concerns by keeping them away from the building envelope



(HX sustaining 200 kPa pressure in 12 mm tubes with a yield factor of safety of 5)

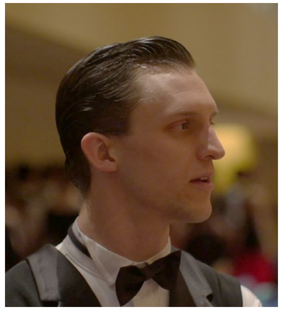
Team

- Treau founded in 2017; renamed to Gradient in 2021
- Awarded over $8 million in government funding and $12 million in venture funding
- IP in unique HVAC system designs and heat exchanger morphologies
- Strong expertise in thermal engineering, system design, and commercialization
- Focused on the development of a high-performance window AC replacement
- **Key Partner: Otherlab**
  - Licensing for additional IP
  - Provides access to machine shop for prototyping

Dr. Vince Romanin, CEO
Over 10 years of heat transfer research; Cyclotron Road fellow

Dr. Jason Wexler, Head of Research
Track record of research commercialization

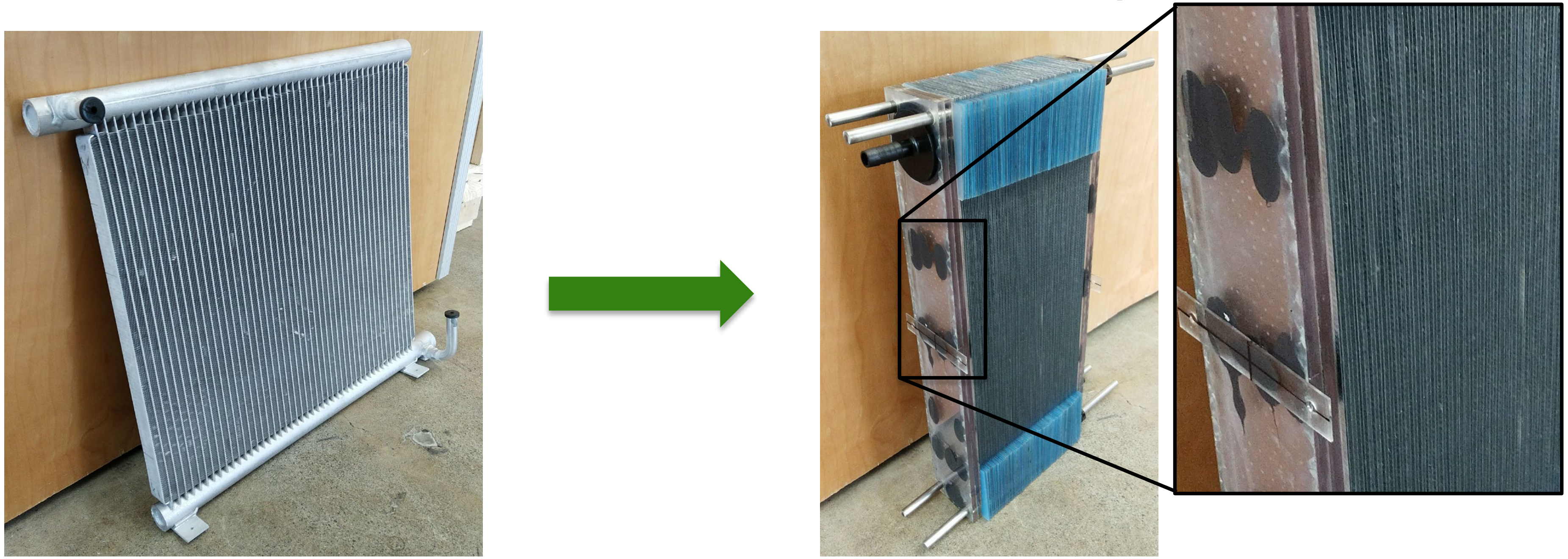
Bataung Mohapi
Mechanical design of polymer heat exchanger components



Dr. Daniel B. Boman
Over 10 years of heat transfer research; heat exchanger design and modeling

Objectives

- Design and demonstrate liquid-air polymer heat exchanger with equivalent heat transfer performance to liquid-air metal heat exchanger



- Demonstrate long-term reliability of polymer film heat exchangers
- Develop manufacturing methods for commercial-scale production of polymer heat exchangers

Approach

Materials

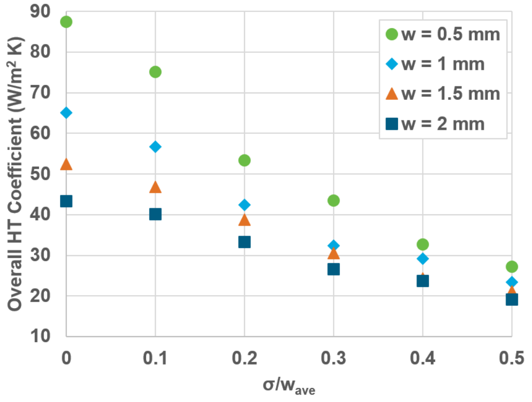
- Weldability
- Reliability
- Permeability

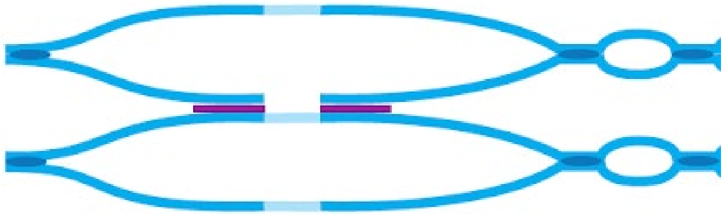
Morphology

- Self-supporting
- High heat transfer coefficient
- Low pressure drop
- High area

Manufacturing

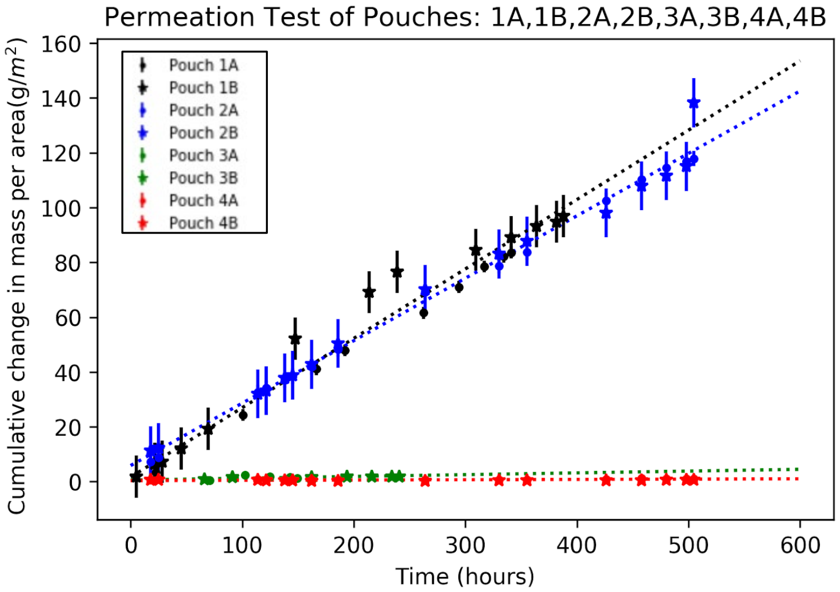
- Film welding
- Pouch manifolding





Materials – Film Selection

- Water-air polymer heat exchangers must exhibit extremely low permeability to water vapor
- Performed permeability tests on pouches made from different films
  - Single-layer polymer (Pouches 1 & 2)
  - Multilayer with metal foil barrier layer (Pouches 3 & 4)
  - Multilayer with metallized polymer barrier layer (Pouch 5)
- **Takeaway: Multilayer films with metal foil barrier layer reduce water loss to acceptable levels**



Note: Pouch 5A and 5B demonstrated changes in mass too high to be shown on the figure

Materials – Multilayer Film Accelerated Aging Testing

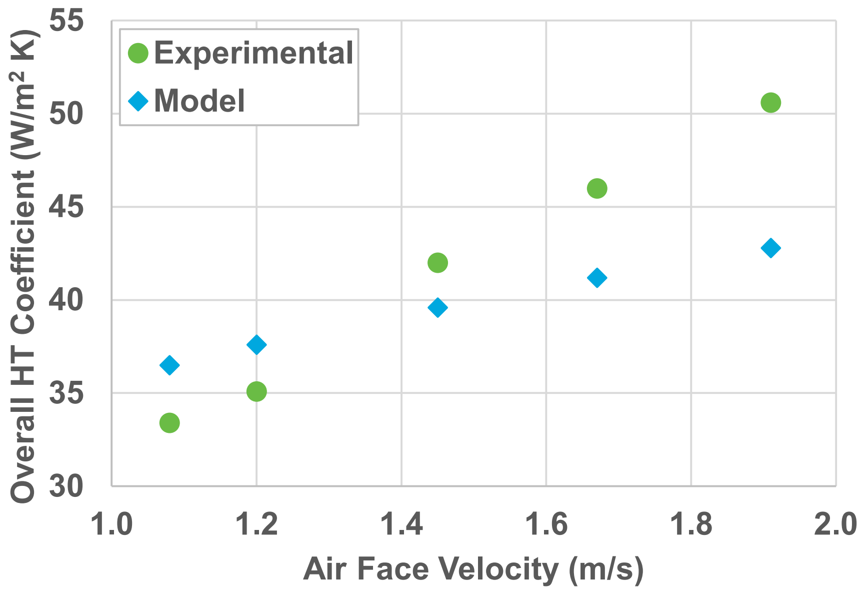
- Film samples are submerged in a water bath at 90 °C and monitored for interlayer delamination until failure
- Time-temperature superposition used to estimate film lifetime at 40 °C

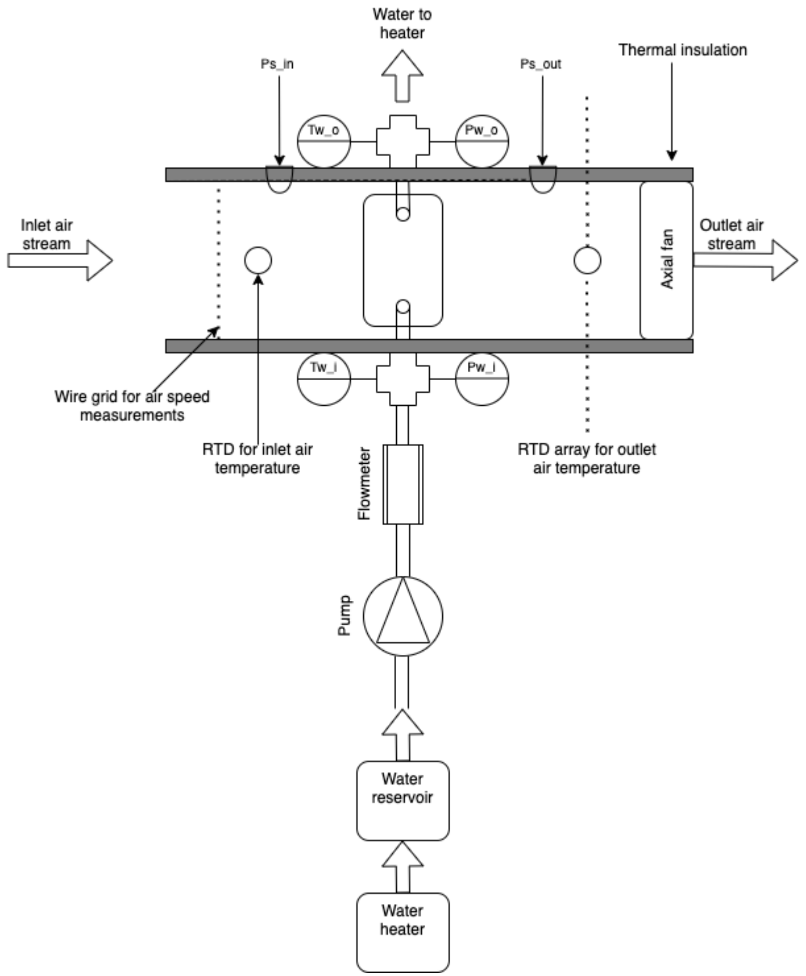
Film Designation	Time to Failure (h)	Estimated Lifetime (years)	Failure Location
1	24	2.3	Between sealing/barrier layers
2	24	2.3	Between sealing/barrier layers
3a	72	6.9	Between barrier/protective layers
3b	96	9.2	Between barrier/protective layers
4a	384	36.6	Between sealing/barrier layers
4b	384	36.6	Between sealing/barrier layers

- **Takeaway: Films 4a and 4b are least susceptible to interlayer water intrusion and delamination**

Morphology – Multilayer Polymer HX Testing

- 86-pouch heat exchanger prototype tested in wind tunnel
- Heat transfer model predicts experimental values to within +10/-15%
- σ/w_{ave} = 0.29 (target 0.1 for 75% improvement in overall HT coefficient)





Manufacturing – Welding Processes

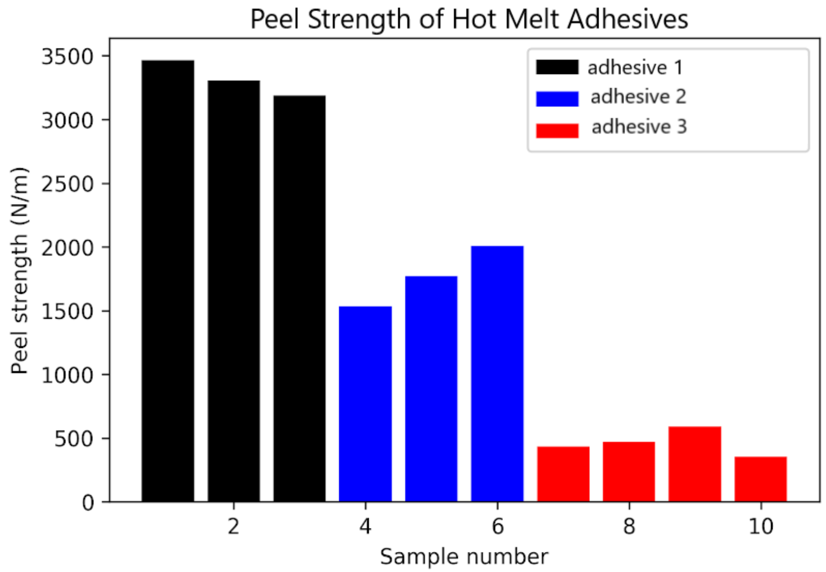
- **Laser Welding**
  - Excellent control over weld features
  - Low tooling costs
  - High capital costs
- **Ultrasonic Welding**
  - Rapid throughput
  - Common process in film packaging industry
  - Compatible with multilayer films

Ultrasonically welded multilayer material sample

Ultrasonically welded multilayer material sample undergoing burst testing at 20 psi

Manufacturing – Manifolding

- Identified five different methods for joining pouches together
  - Liquid adhesives, impulse welding, induction welding, solvent welding, hot melt
- Hot melt adhesives demonstrated high strength but failed rapidly when subjected to heated water



- **Takeaway: Sealants provide reliable and robust seal necessary for polymer heat exchanger manifolding**

Manifolding technique	Submerged temperature	Average failure time
Hot melt adhesive	50 °C	17 s
Sealant	85 °C	74377 s

Impact

- Initial technoeconomic modeling: Polymer heat exchanger that fits in same envelope as metal liquid-air heat exchanger and offers similar performance **costs 45-75% less**
- Short term: low-cost liquid-air HX can enable Gradient's economical indirect-coupled heat pump
  - Increases potential for use of higher performing, low-GWP refrigerants
  - Allows user installation of systems with equivalent heating and cooling performance to mini-split
  - **~2x reduction in lifetime CO2eq** compared to window AC + combustion heat
- Long term: polymer heat exchanger can be sold to other OEMs to enable efficiency improvements in electric heat pumps, furnaces, and building hot water

Stakeholder Engagement

- **Suppliers**
  - Strong collaboration with welding equipment vendor
  - Close relationships with multiple materials vendors to develop novel materials for polymer heat exchangers
- **Regulators**
  - Representatives on UL and ASHRAE committees to define future directions for HVAC equipment
- **Customers**
  - Direct-to-consumer sales planned for user-installed heat pump (shown on previous slide)
  - Conducted conjoint analysis to define customer value proposition and willingness to pay
  - Continuous customer feedback through beta program

Conclusions & Remaining Work

- **Appropriate polymer film structure for low water loss was determined**
- **Multilayer polymer films with long life identified and selected**
- **Moderate heat transfer performance demonstrated at bench scale; paths for further improvement identified**
- **Remaining work**
  - Develop self-supporting inflatable polymer structure that produces low variability in channel spacing
  - Continue manifolding development to mitigate possibility of delamination
  - Demonstrate full-size heat exchanger prototype with equivalent performance to metal liquid-air heat exchanger
  - Evaluate condensate drainage during cooling operation and explore surface treatments to minimize effects on performance

Thank You

Gradient
Dr. Jason Wexler
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REFERENCE SLIDES

Project Budget

Variances: Funds from equipment reallocated to consultants and materials to allow for additional prototyping and computational studies

Cost to Date: $317,850

Budget History					
FY 2020 (past)		FY 2021 (current)		FY 2022 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$549,120	$0	$450,879	$0	$0	$0

Project Plan and Schedule