High Temperature Ceramic Heat Exchanger for Solid Oxide Fuel Cell

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DOE Award No.: DE-FE0024090
DOE Program Manager: Sydni Credle, Ph.D.
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MiTi: What We Do

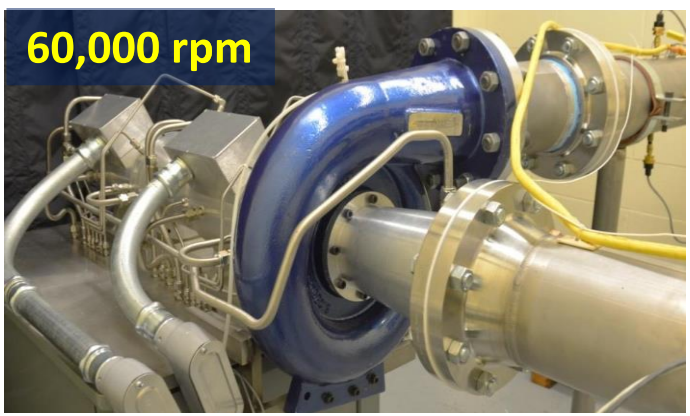
ORC Turbogenerator

Air Cycle Machine

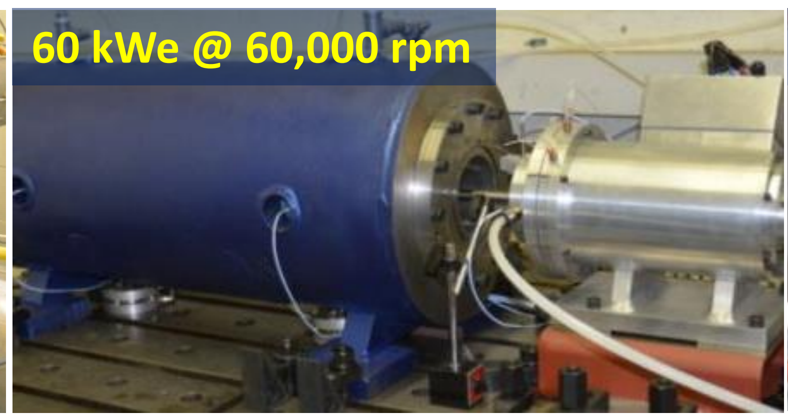
Hydrogen Blower

Fuel Cell Compressor

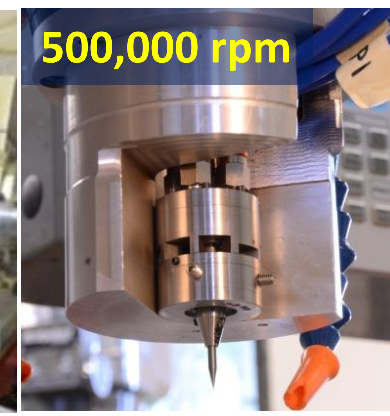
Hydrogen Pipeline Compressor



Flywheel Electromechanical Battery



Micro Machining



By Use of Ultra High Speed, We Deliver Compact, Power-Dense Engines!

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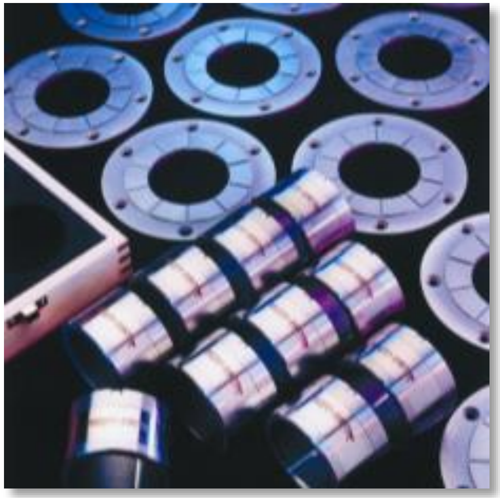
At the Core: MiTi's Advanced Foil Bearings

Generation IV and V Foil Bearings



- Oil-Free ⬄ Maintenance/Contamination Free
- Ultra High Speed: Proven to 1,000,000 rpm
- With Korolon® 1350/2250 ⬄ High Temperature Operation ⬄ Turbine Exhaust Conditions, up to 810ºC (1500ºF)
- Negligible Friction Power Loss ⬄ High Mechanical Efficiency

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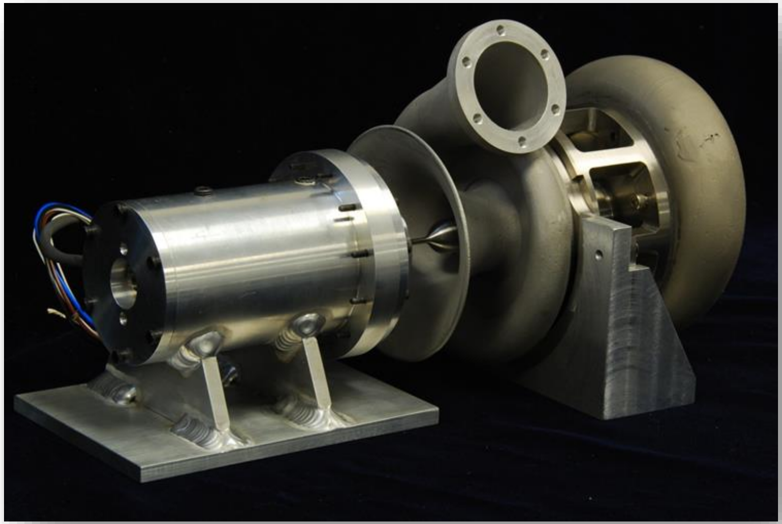
Background

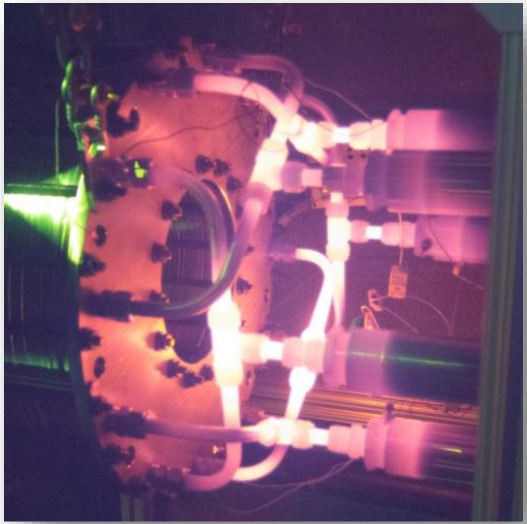
MiTi® 8 kW Turboalternator

- 1.6 kW/kg (1 hp/lbm)
- Oil-free foil bearings/Process-air lubricated
- Design speed: 184,000 rpm
- 12% Thermal Efficiency (Unrecuperated)



Recuperator

- Low pressure drop: < 3 psi
- High Effectiveness: $\varepsilon \approx 0.9$
- Radial geometry fits around combustor
- Increase in Thermal Efficiency from 12 to 33%



References:

- Heshmat, H., Walton, J. F., and Hunsberger, A., "Oil-Free 8 kW High-Speed and High Specific Power Turbogenerator," Proceedings of ASME Turbo Expo 2014, GT2014-27306
- Córdova, J. L., Walton, J. F., and Heshmat, H., "High Effectiveness, Low Pressure Drop Recuperator for High Speed and Power Oil-Free Turbogenerator", Proceedings of ASME Turbo Expo 2015, GT2015-43718

Project Team

Mohawk Innovative Technology, Inc.

- Hooshang Heshmat, Ph.D.
  - Technical Director
  - Principal Investigator
- James F. Walton II
  - Sr. Program Manager
- Jose L. Cordova, Ph.D.
  - Program Manager
  - Project Engineer

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

- Hossein Ghezel-Ayagh, Ph.D.
  - FCE Lead
- Micah Casteel, Ph.D.
  - Mechanical Engineer
- Stephen Jolly
  - Systems Design Engineer

Objective

- Develop a High Heat Transfer Effectiveness, Low Pressure Drop *Ceramic* Heat Exchanger for Application as Solid Oxide Fuel Cell Cathode (SOFC) Air Preheater.
  - Possible Materials: Ceramics, Cermet, Hybrid Ceramics, Elastic Ceramics

Purpose of Heat Exchanger

- SOFC cathode requires a fresh air supply at ~700^{o}C for operation.
- Anode exhaust contains CO and H_2.
  - These are post-combusted in a catalytic oxidizer, yielding high temperature heat.
  - Heat is recovered in *heat exchanger* and used to preheat supplied air.

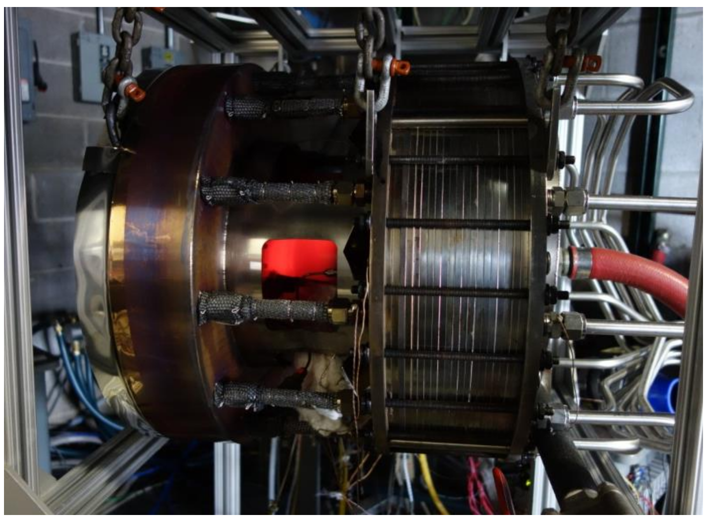
(Continued)

Motivation for Use of Ceramics

- Humidity in air supply causes metal alloys (e.g.: steels, nickel-based and other super-alloys) used in typical heat exchangers to release volatilized chromium.
  - Chromium reacts with cathode materials to degrade cell voltage and ultimately poison cathode elements.
- Alternate materials (i.e., ceramics, cermets, hybrid ceramics, elastic ceramics) may offer best choice for SOFCs.

Overview of Approach

- Leverage MiTi's Novel Gas Turbine Recuperator
  - Original application: 8 kW gas turbine-based turboalternator
    - Turbine engine specifications, operating at 42 psi, allowed pressure drop of 3 to 5 psi.



  - Attained 90% heat transfer effectiveness (measured) at engine operating conditions.
  - Greater than Two-Fold Increase of Cycle Thermal Efficiency
    - from 12% to 30% (measured)

- Extend Technology to SOFC
  - Ceramic Materials
  - Reduce pressure drop

Major Program Elements

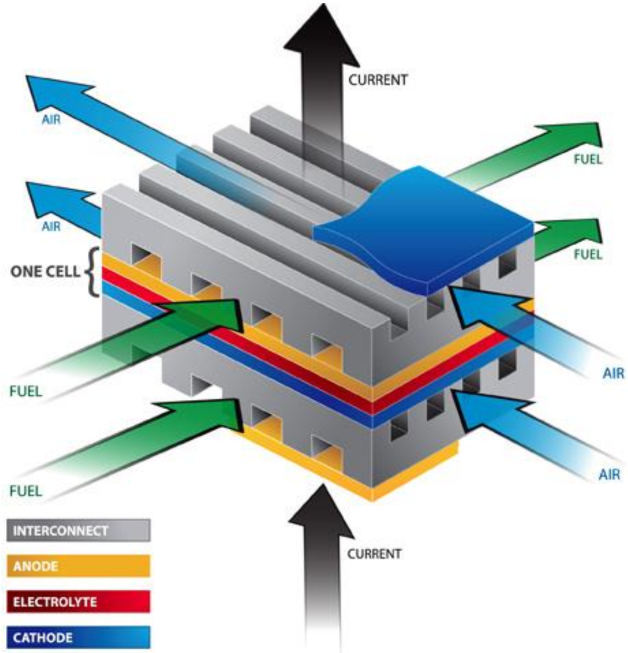
1. Solid Oxide Fuel Cell Definition of Requirements
2. Heat Transfer Analysis and Heat Exchanger Sizing
3. Ceramic Materials Review and Selection
4. Fabrication of Heat Exchanger Prototype
5. Pressure drop and thermal performance testing
6. Integration to SOFC test facility

Target Application: Solid Oxide Fuel Cell Operating Conditions

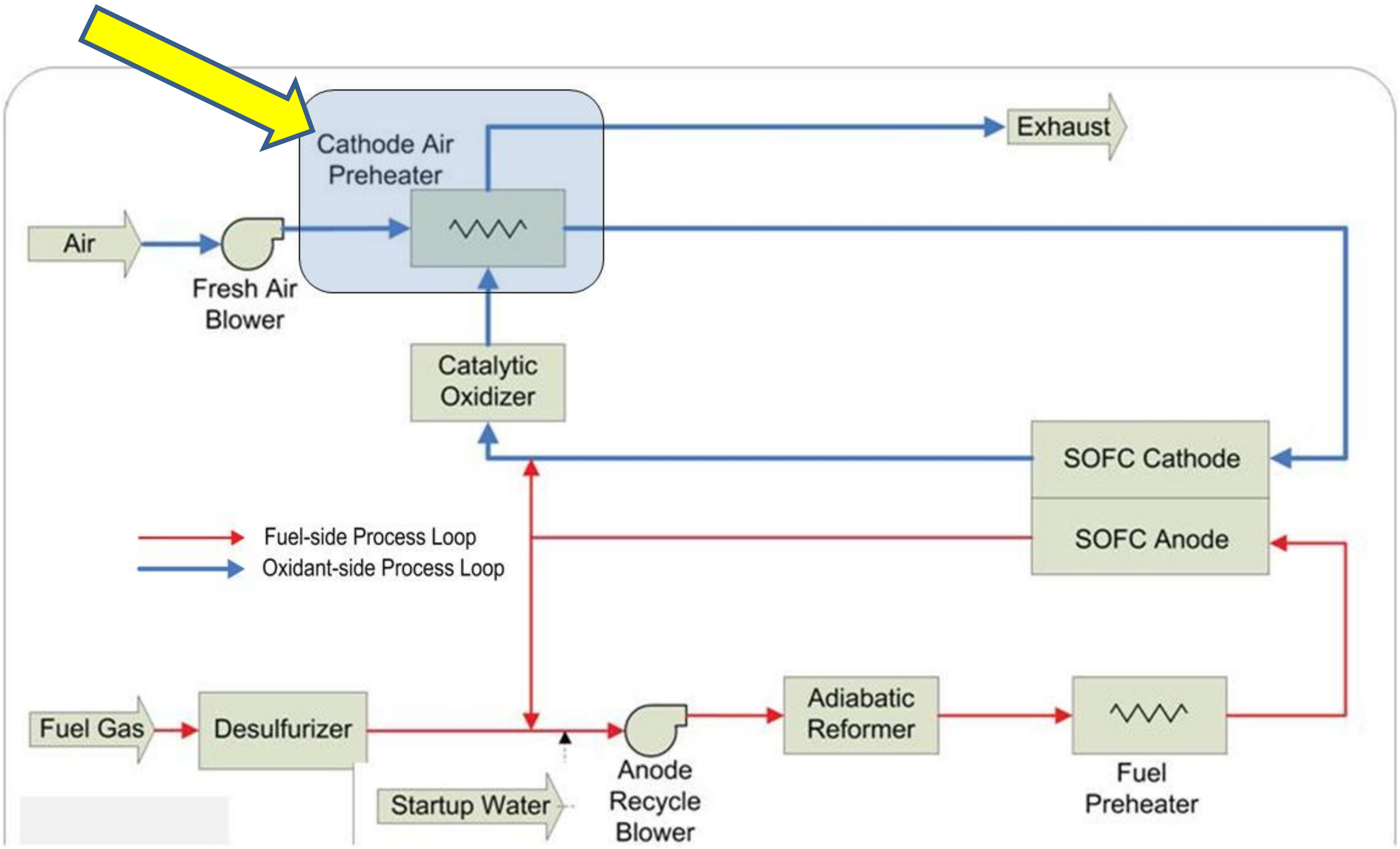
IDENTIFICATION OF TARGET SOFC AND PROTOTYPE REQUIREMENTS

Target Application

- FuelCell Energy Inc.
  - Proof Of Concept (POC) 50 kW_e SOFC



SOFC System Schematic



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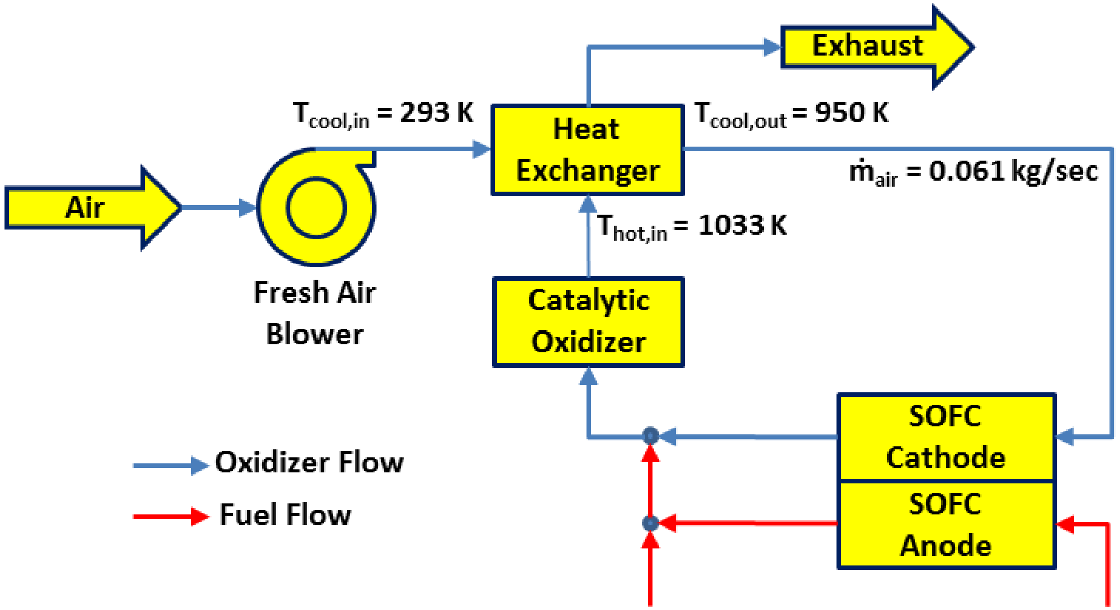
50 kWe POC Operating Conditions



- Required Preheater Heat Transfer:

$$Q = \dot{m}\, c_p\, (Tair_{out} - Tair_{in}) \approx 41 \text{ kW}$$

- Total Allowable Pressure Drop:

$$\Delta P_{tot} = 3447.4 \text{ Pa } (= 13.8 \text{ inH}_2\text{O} = 0.5 \text{ psi})$$

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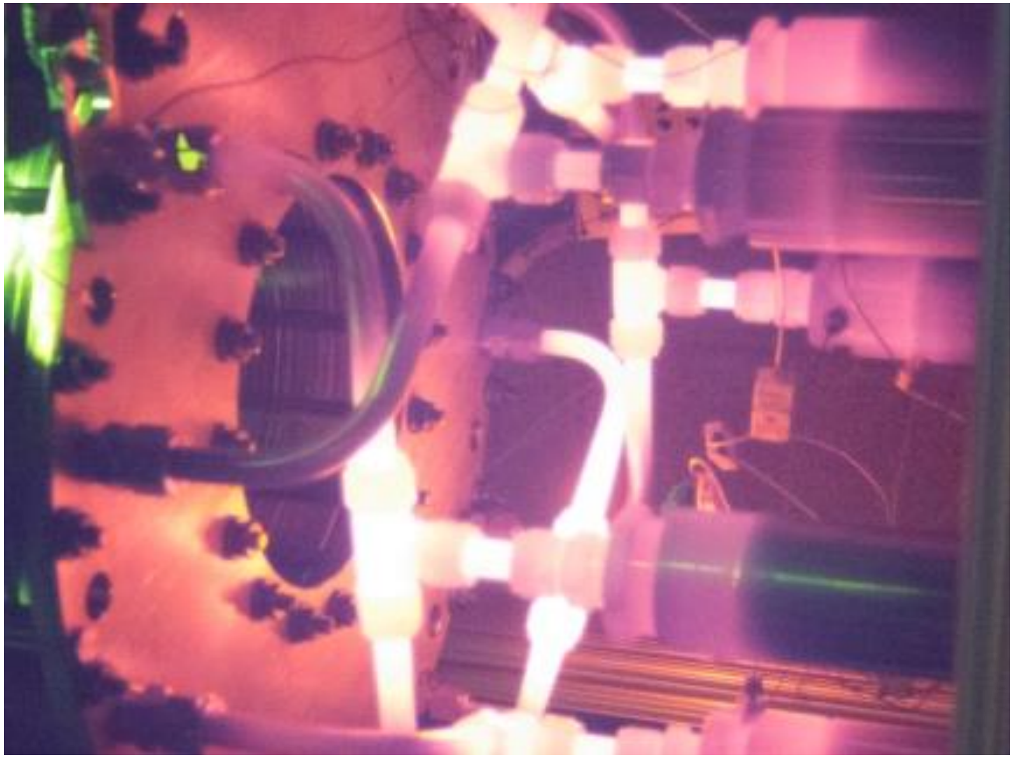
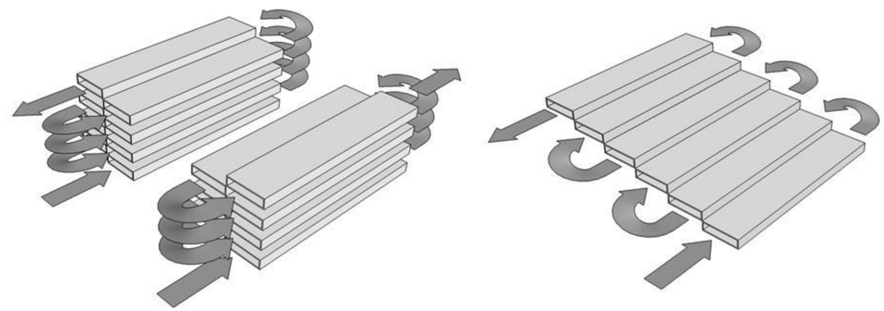


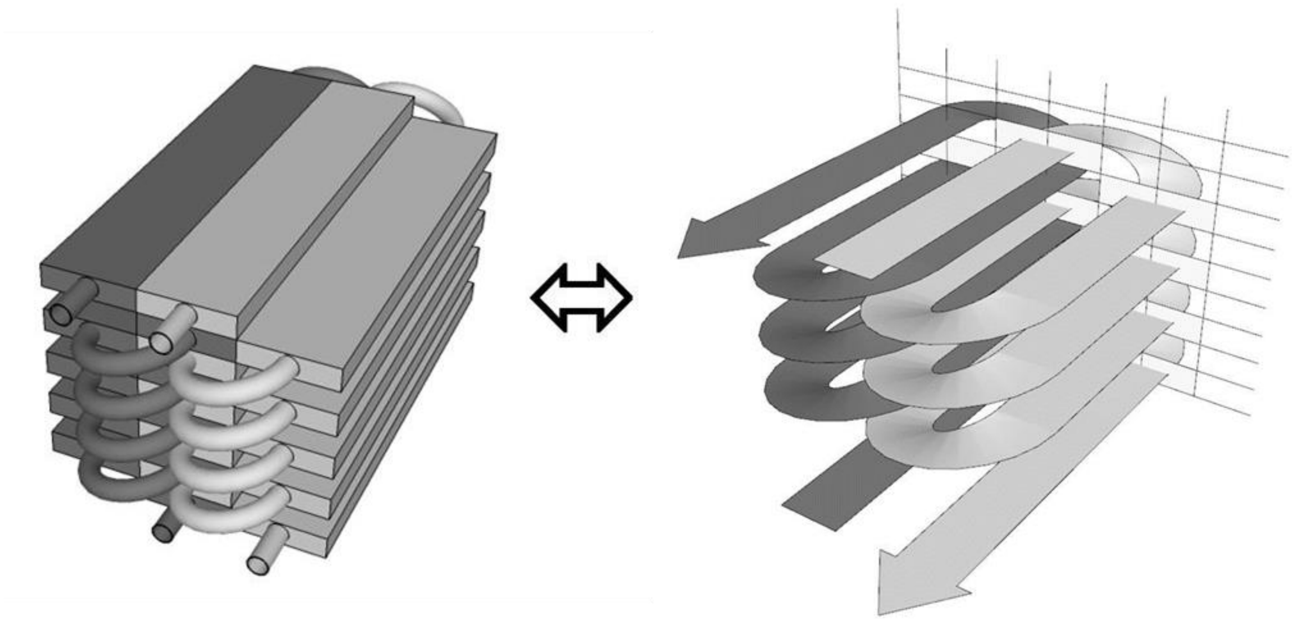
Background

MiTi’S RECUPERATOR EXPERIENCE

MiTi's Recuperator Concept

- Overlapping quasi-helical flow paths
  - ***Patent Pending: U.S. Provisional Patent Application US62/040,559***





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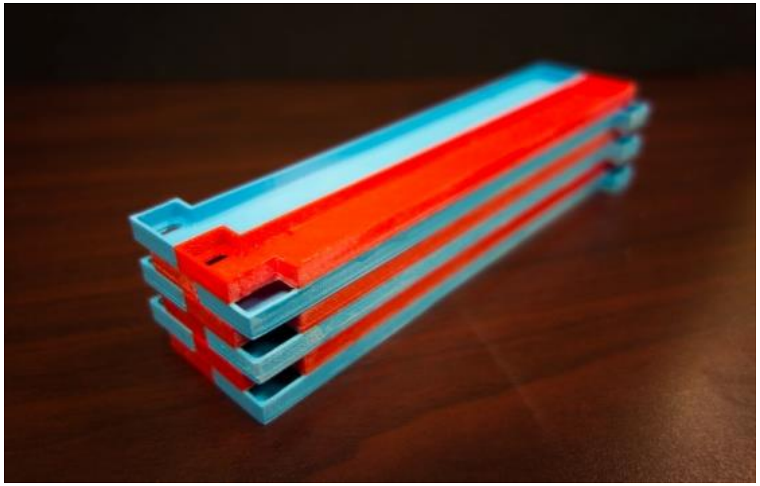
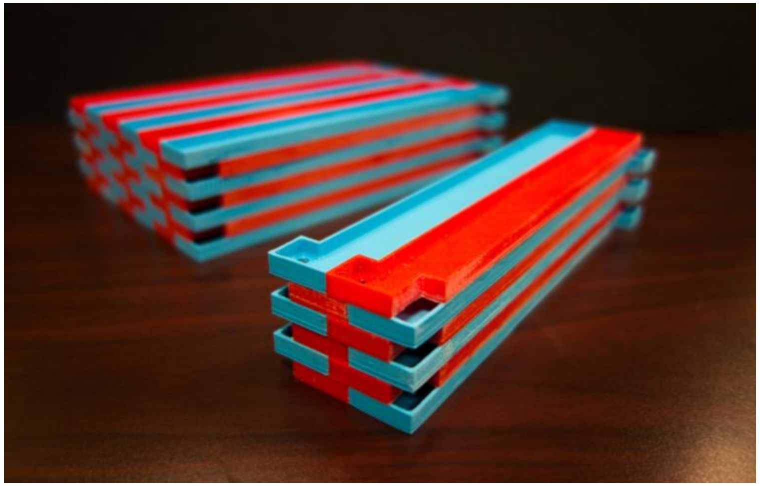
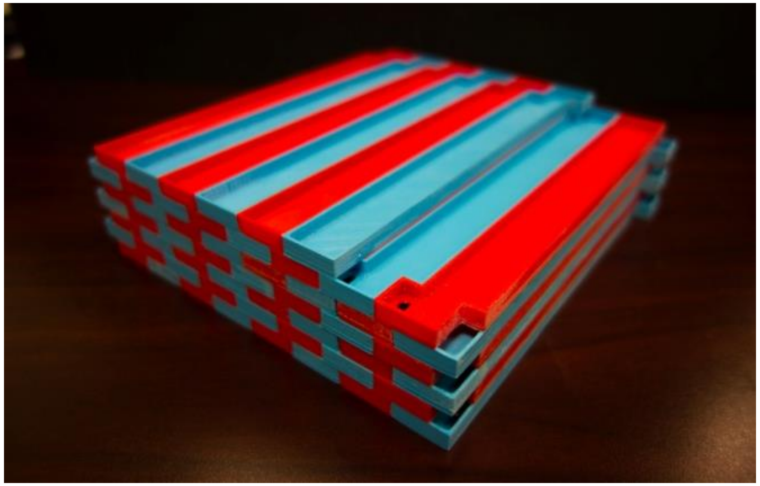
MiTi's Recuperator Concept







Design allows to add or remove segments according to flow, pressure drop, or heat exchange rate requirements.

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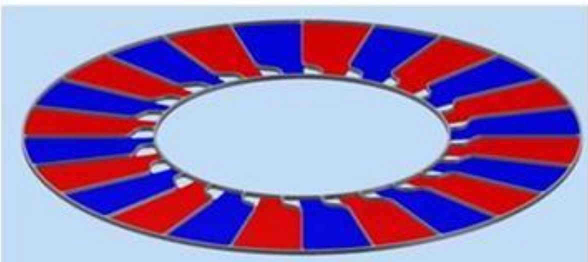
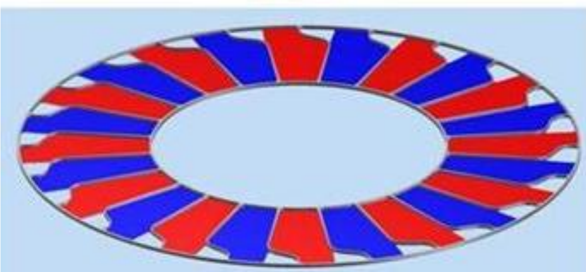
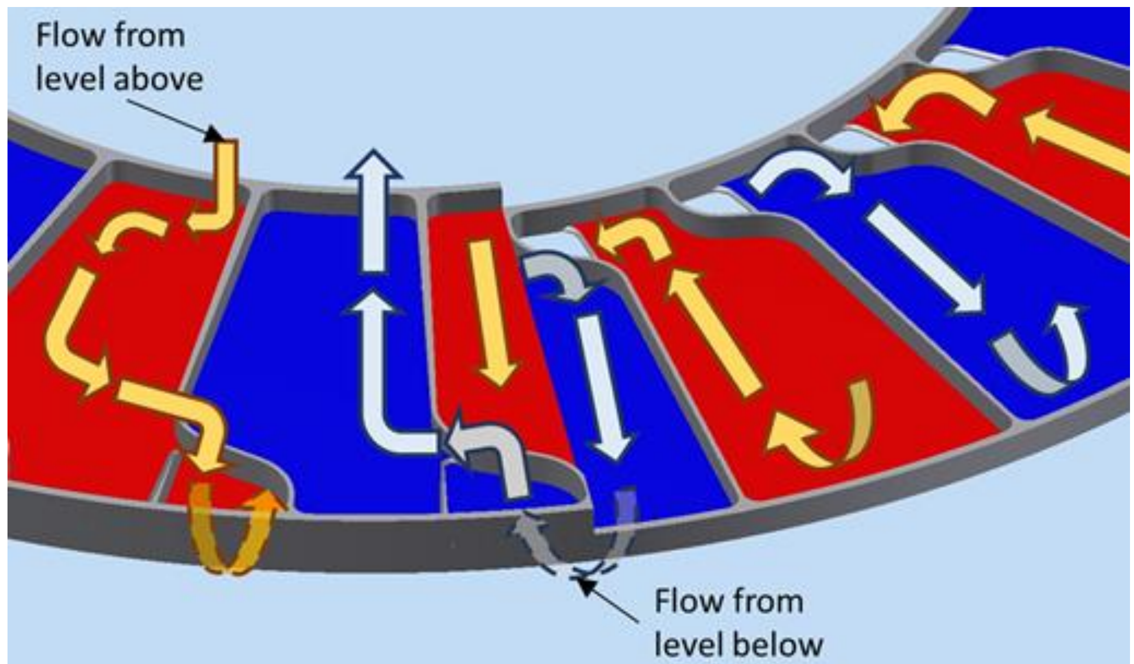
Patent Pending Design

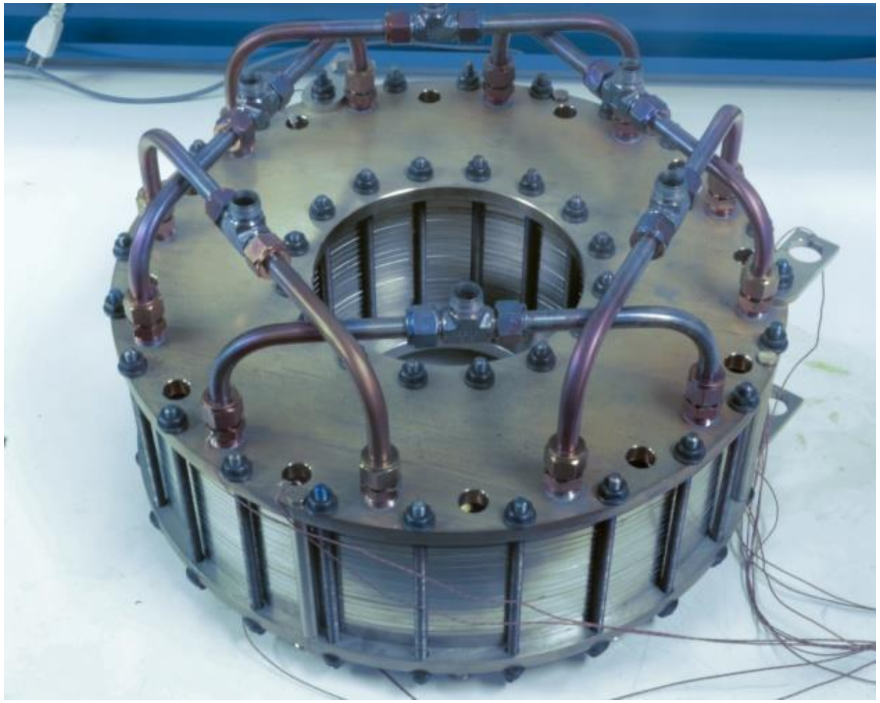
- Passages formed by stack of trays with wedge-shaped passage segments
  - Two types of trays: alternating openings at inner/outer radius
  - Openings turn the flow to diagonally adjacent wedge ⇔ chessboard pattern

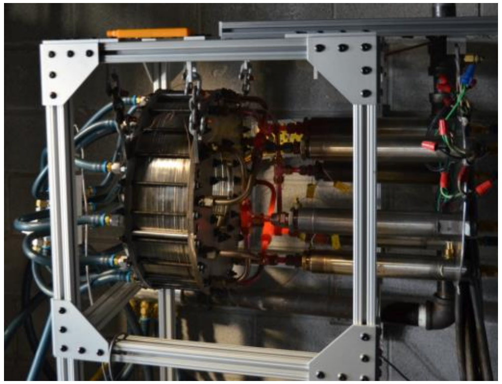


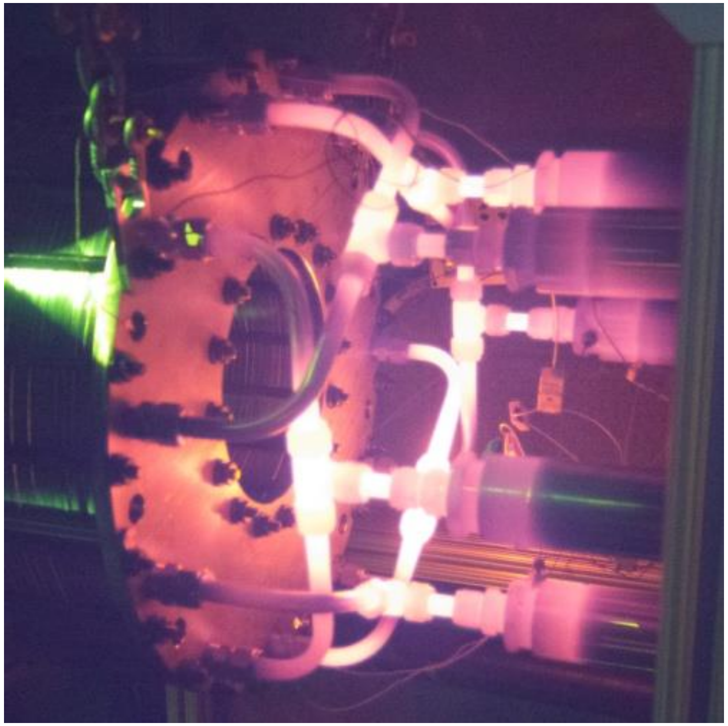


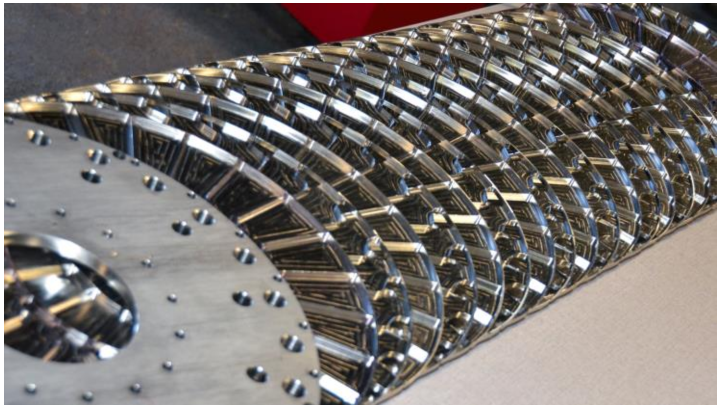


Recuperator Prototype









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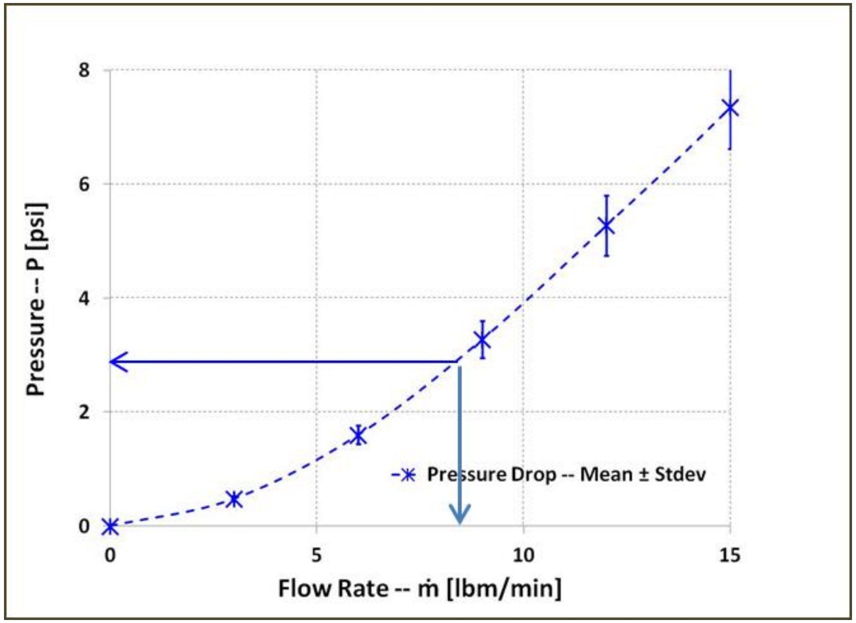
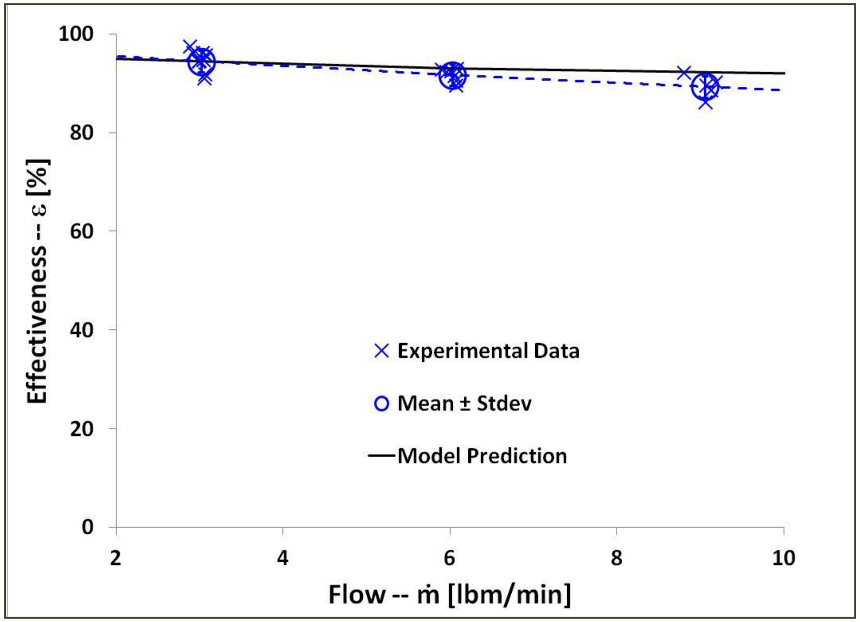
Experimental Performance

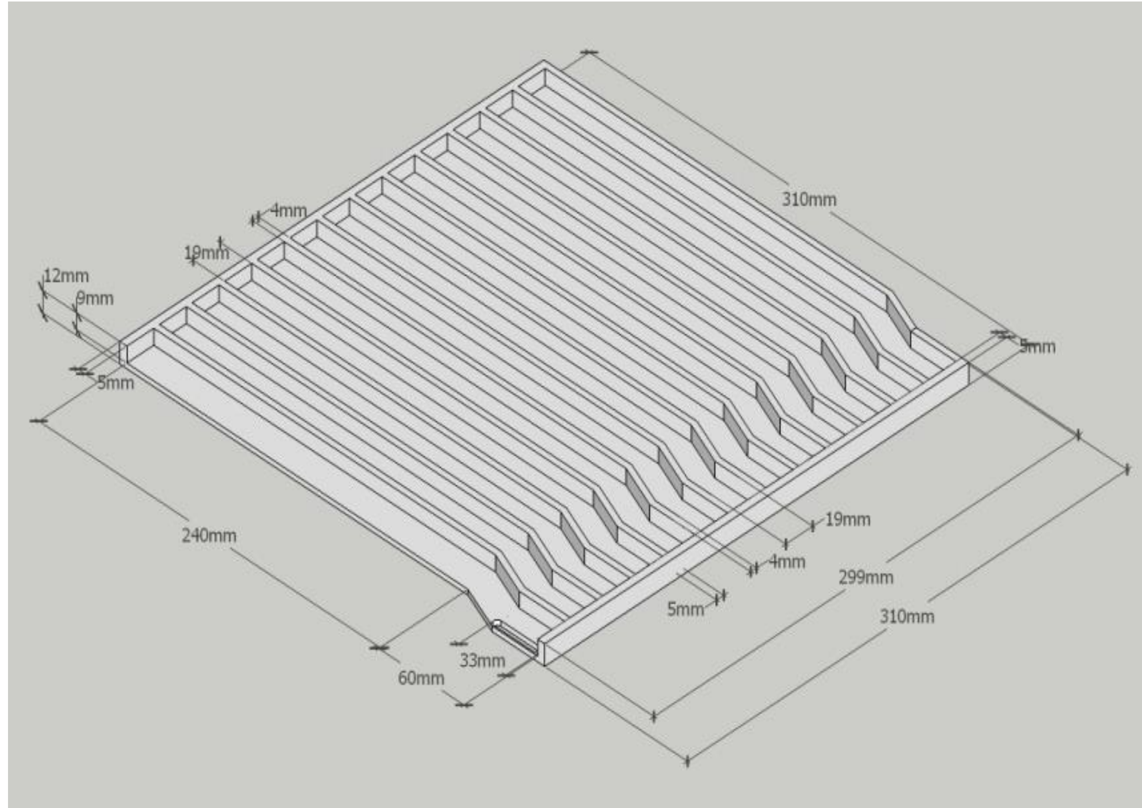
Pressure Drop (ΔP vs. ṁ)



Effectiveness (ε vs. ṁ)



$$\varepsilon_R = \frac{(\dot{m}\,c_p)_{\mathrm{h}}(T_{\mathrm{h,in}} - T_{\mathrm{h,out}})}{(\dot{m}\,c_p)_{\mathrm{min}}(T_{\mathrm{h,in}} - T_{\mathrm{c,in}})} = \frac{(\dot{m}\,c_p)_{\mathrm{c}}(T_{\mathrm{c,out}} - T_{\mathrm{c,in}})}{(\dot{m}\,c_p)_{\mathrm{min}}(T_{\mathrm{h,in}} - T_{\mathrm{c,in}})}$$



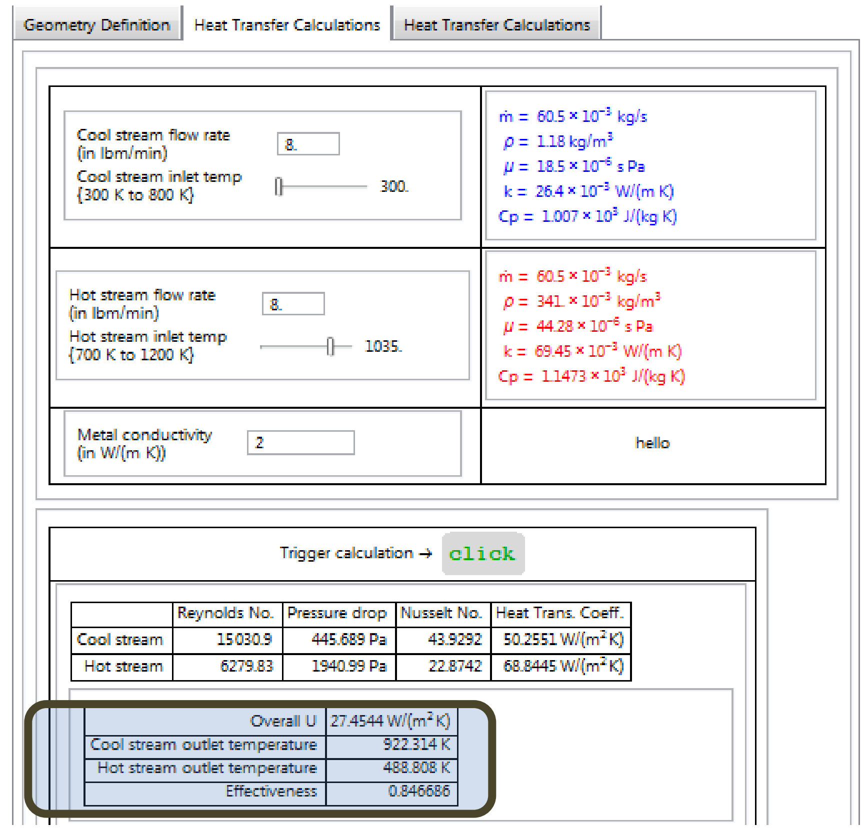
Heat Transfer Analysis and Heat Exchanger Sizing

HEAT EXCHANGER DESIGN

50 kWe POC Heat Exchanger Design

- MiTi's Modeling/Design Tool
  - Written in *Mathematica*
  - Solves fundamental heat transfer governing equations

- First Iteration Sizing Results:
  - Preheated air temperature $Tair_{out} = 1200°F$
  - Pressure drop $\Delta P = 0.33$ psi
  - Effectiveness = 85%



Overall U	27.4544 W/(m² K)
Cool stream outlet temperature	922.314 K
Hot stream outlet temperature	488.808 K
Effectiveness	0.846686

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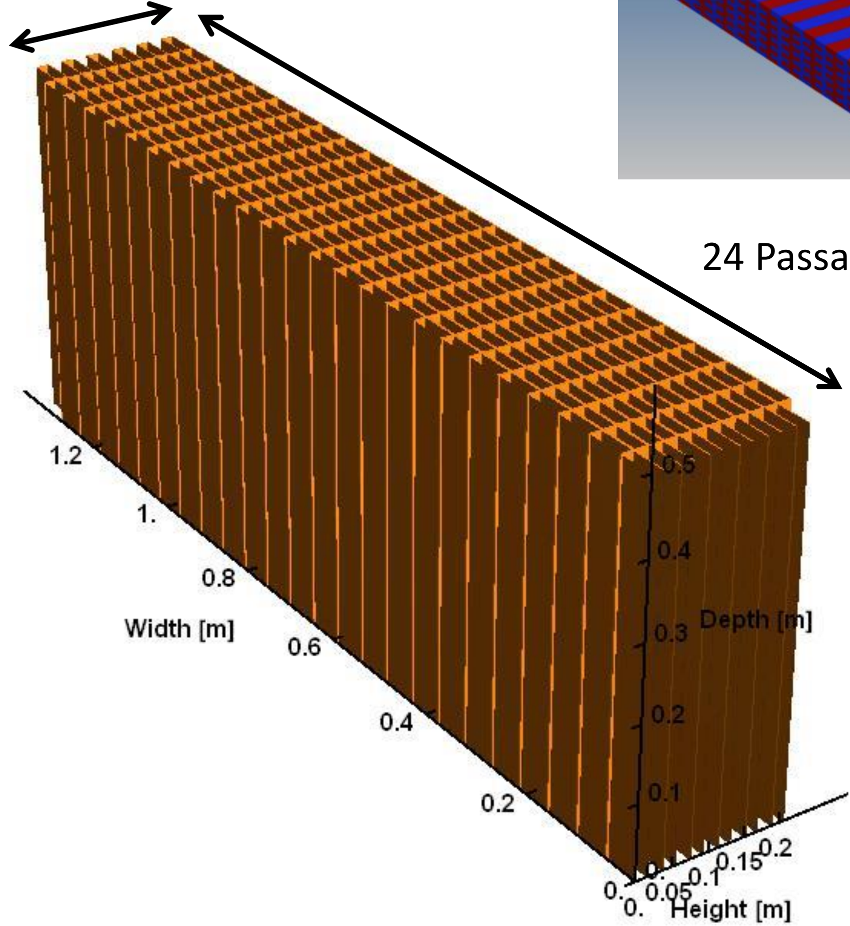
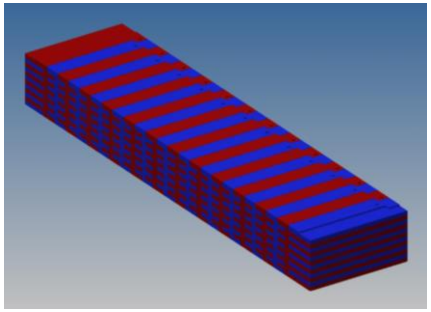
A Conceptual Heat Exchanger Layout

- Subdivide hot and cold flow into 12 Passages Each (Total of 24 Passages Wide),
- Make Stack of 12 Layers Deep
- Geometry of heat exchange elements:
  - Total length single flow path: 6.0 m
  - Wall thickness: 0.004 m
  - Passage width: 0.05 m
  - Passage height: 0.015 m





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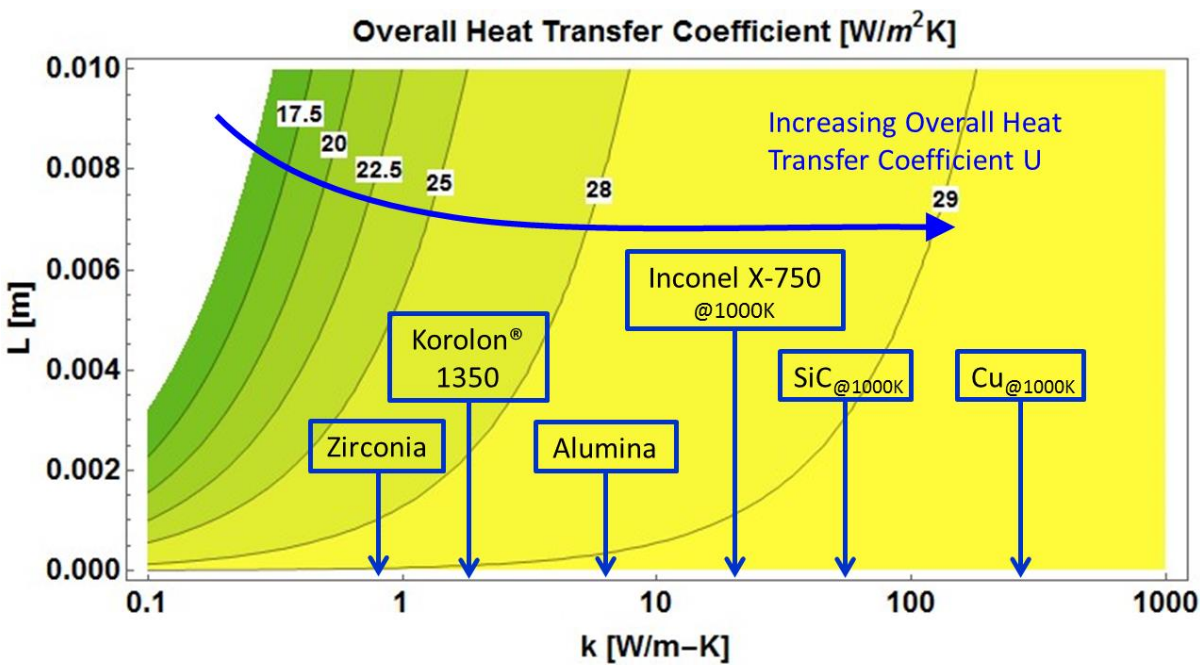


Thermal Criterion for Material Selection

MATERIAL SELECTION

Parametric Study for Design Optimization

Basic Heat Transfer Element

Cool Stream
- **Conv. Coff.: h_c**
- **Temp.: T_c**

Hot Stream
- **Conv. Coff.: h_h**
- **Temp.: T_h**

Walls:
- **Thickness: L**
- **Conductivity: k**

Preliminary Sizing:

	Heat Trans. Coeff.
Cool stream	50.2551 W/(m^{2}K)
Hot stream	68.8445 W/(m^{2}K)

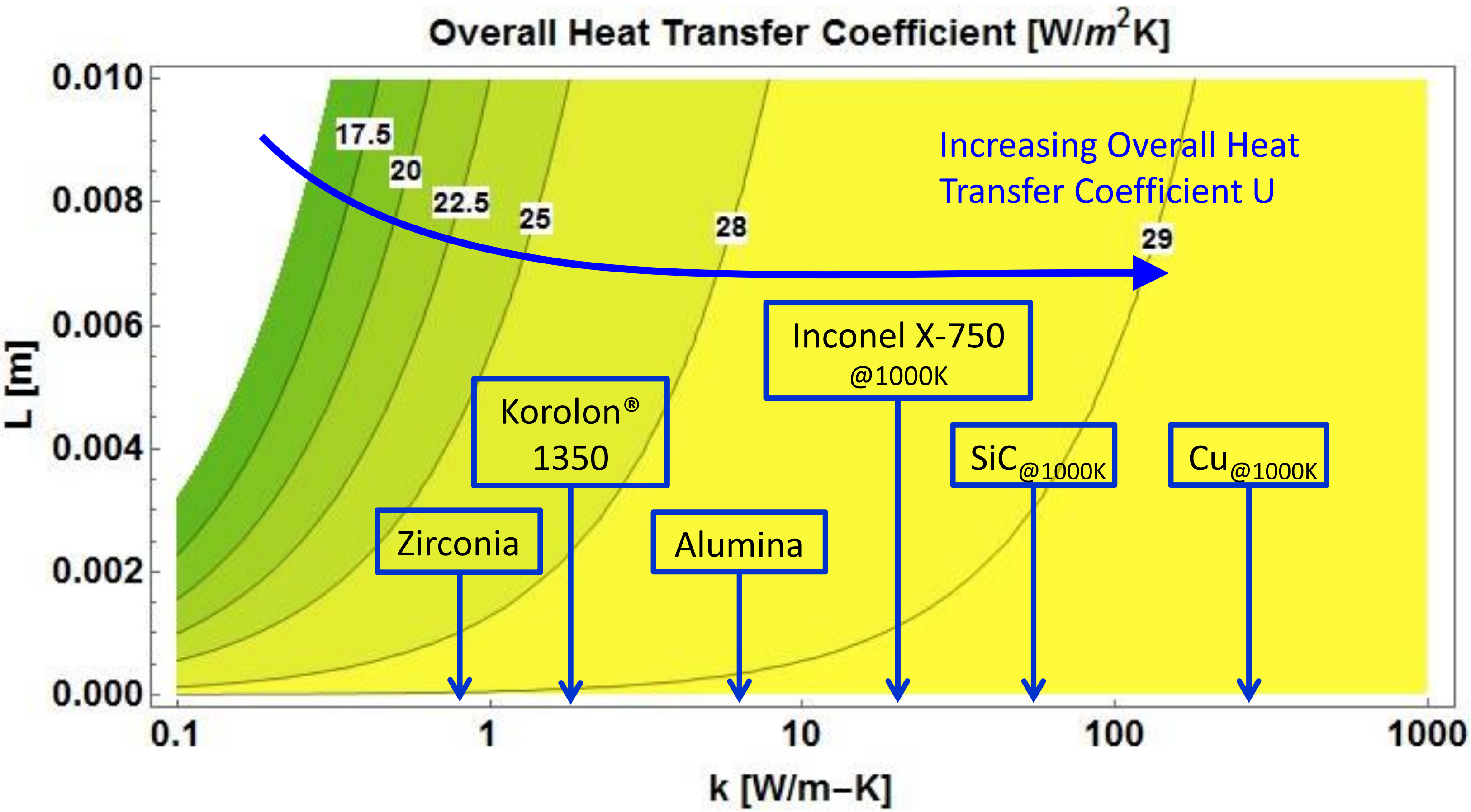
Heat transfer between flows:

$$q = U\,A\,\Delta T = \frac{A\,(T_h - T_c)}{\frac{1}{h_h} + \frac{L}{k} + \frac{1}{h_c}}$$

Overall Heat Transfer Coeff.:

$$\Rightarrow U = \frac{1}{\frac{1}{h_h} + \frac{L}{k} + \frac{1}{h_c}}$$

Effect of Wall Thermal Conductivity



At SOFC operating conditions and practical wall thickness (L < 0.005 m), the walls behave as thermally thin, and the overall heat transfer coefficient is nearly *independent of wall conductivity,* therefore, the choice of material is irrelevant.

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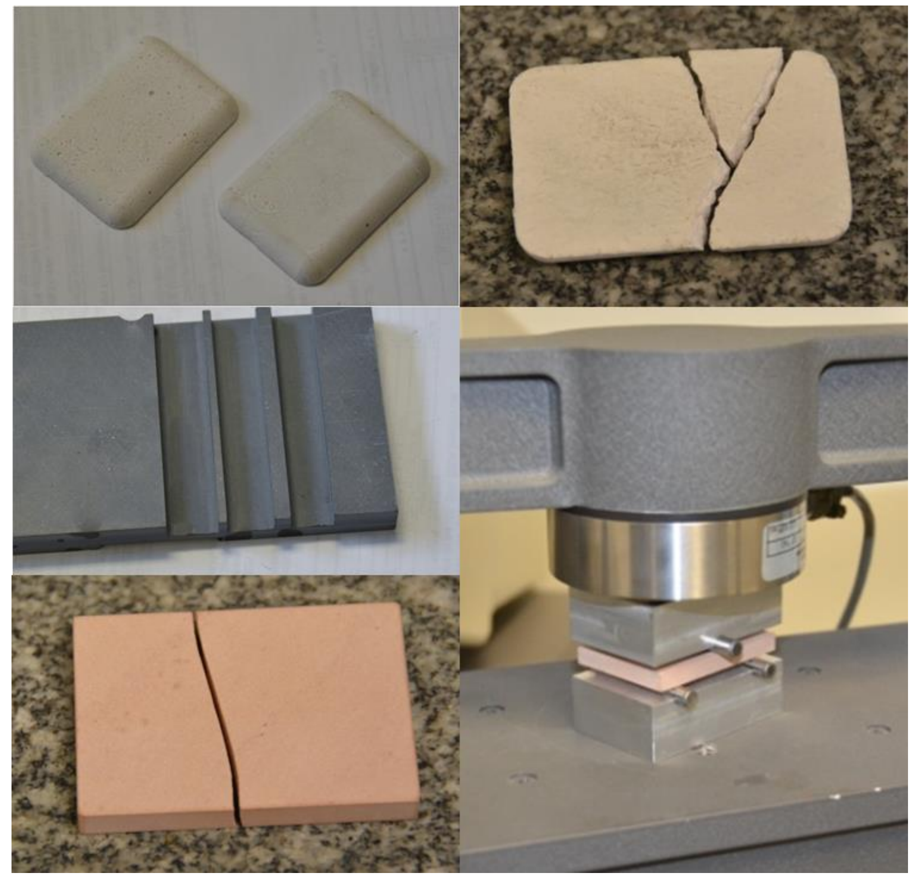
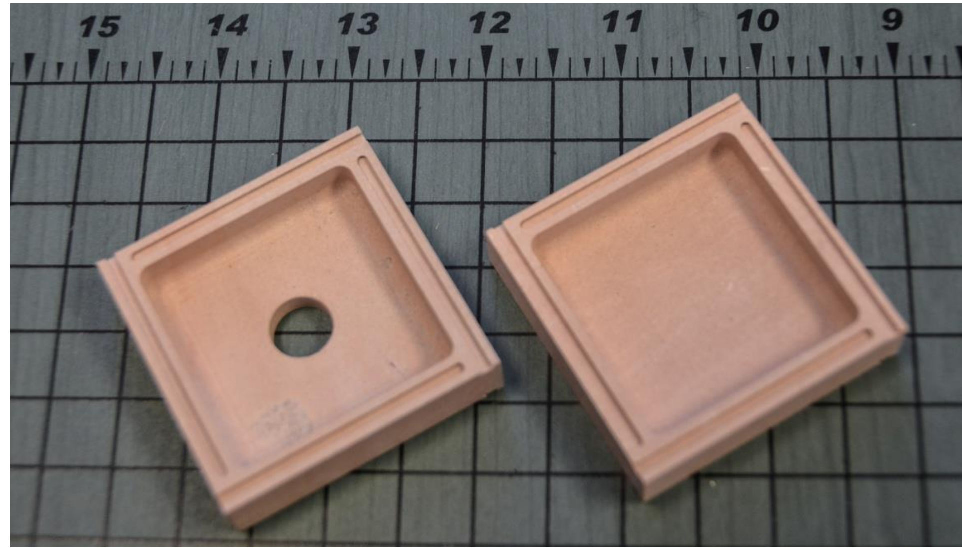
Choice Based on Ease of Fabrication

- Explored several commercially-available materials
  - Castable/Moldable
  - Green-State Machinable
  - Fired-State Machinable
- Fabricated and tested samples



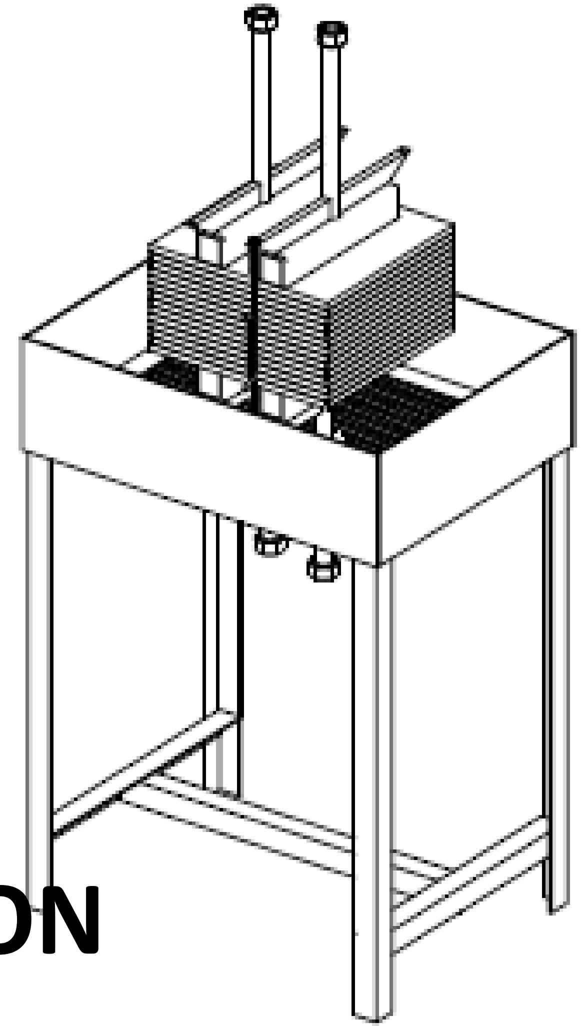
Component Fabrication Testing

- Material Selected: Alumina-Silicate Green-State Machinable
  - Mechanical properties achieved after firing
    - Thermal Cond.: k = 1.45 W/m-K
    - Density: ρ = 2350 kg/m3
    - Flexural stress: s = 69 Mpa
    - Thermal expansion: $\varepsilon = 4.9\ 10^{-6}/^{o}C$
    - Geometric tolerance: 1%



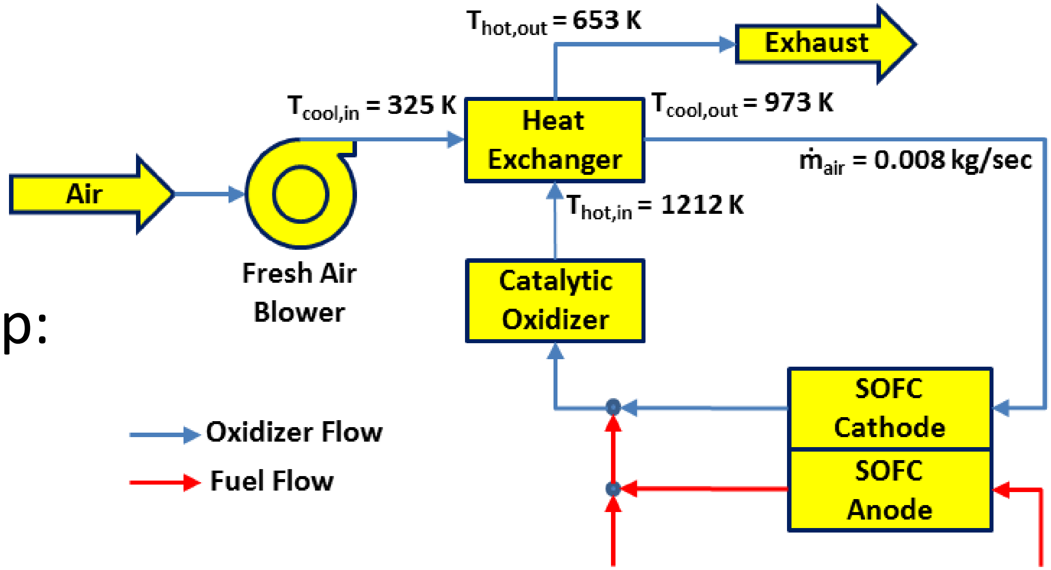
Sizing, Design, and Fabrication

PROTOTYPE INTEGRATION



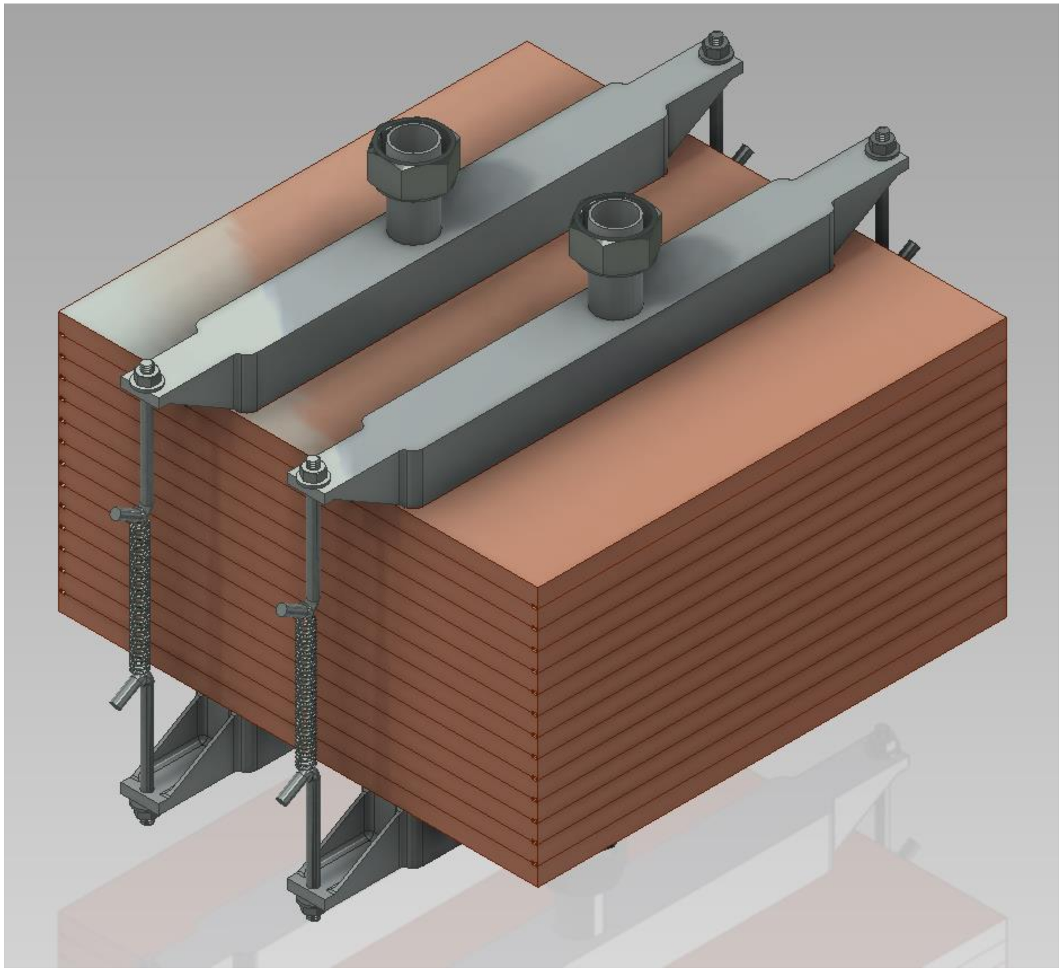
5 kW Prototype Operating Conditions

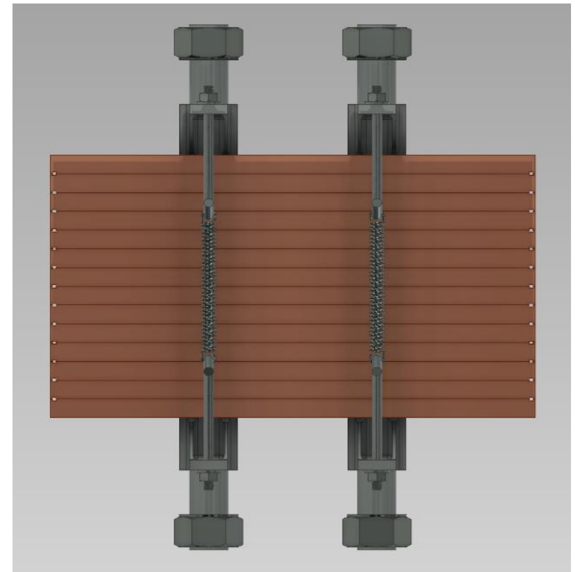
- $\dot{m}$ = 8 g/sec (1 lbm/min)
- Required Heat Transfer:
  - $Q = \dot{m}\, c_p\, (Tair_{out} - Tair_{in}) \approx 5.2$ kW
- Total Allowable Pressure Drop:
  - $\Delta P_{tot} < 3.45$ kPa (0.5 psi)

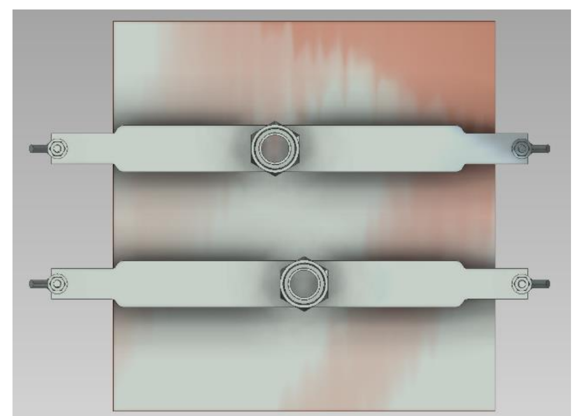


- **With all temperatures pre-determined, the effectiveness is constrained to be ε = 73%**

MiTi® Cathode Air Preheater







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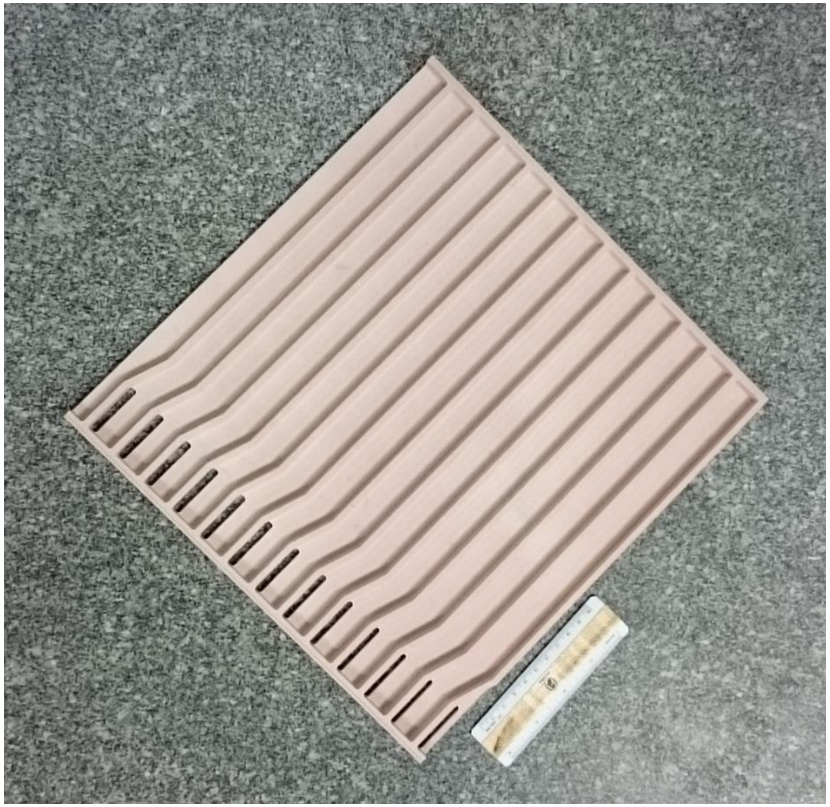
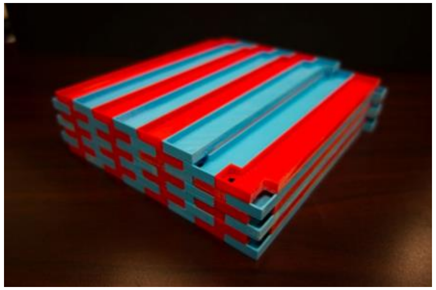
Repeating Unit





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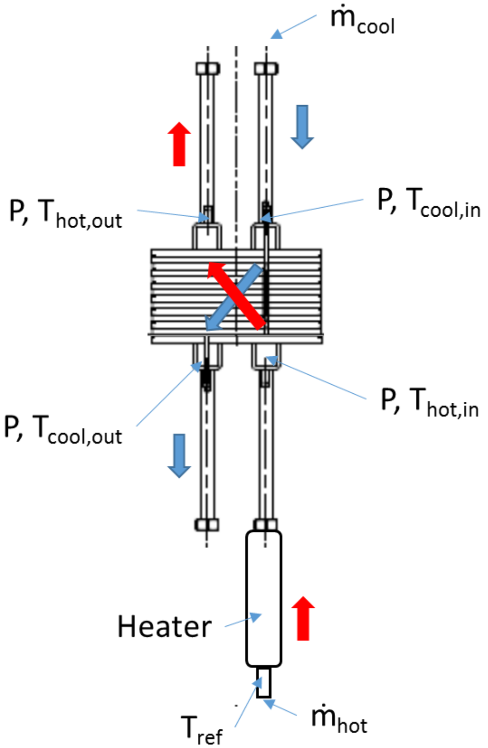
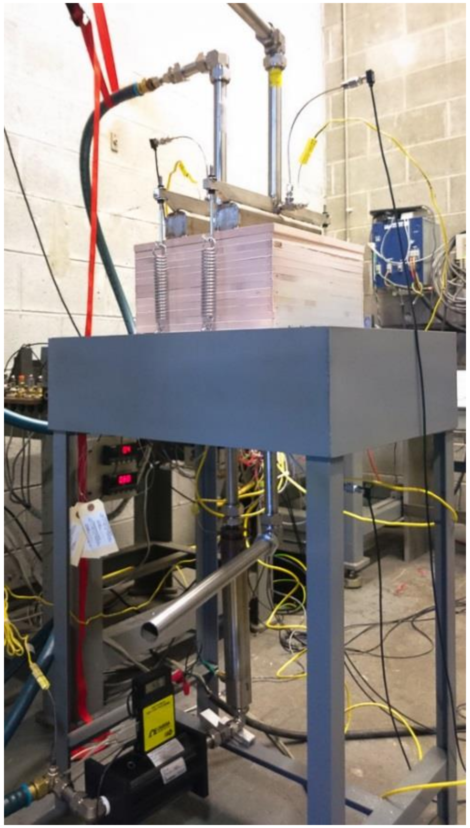
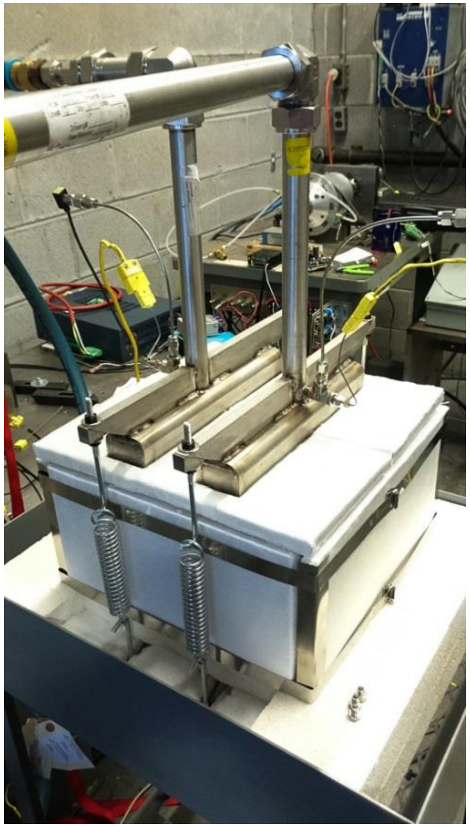
Assembled Prototype







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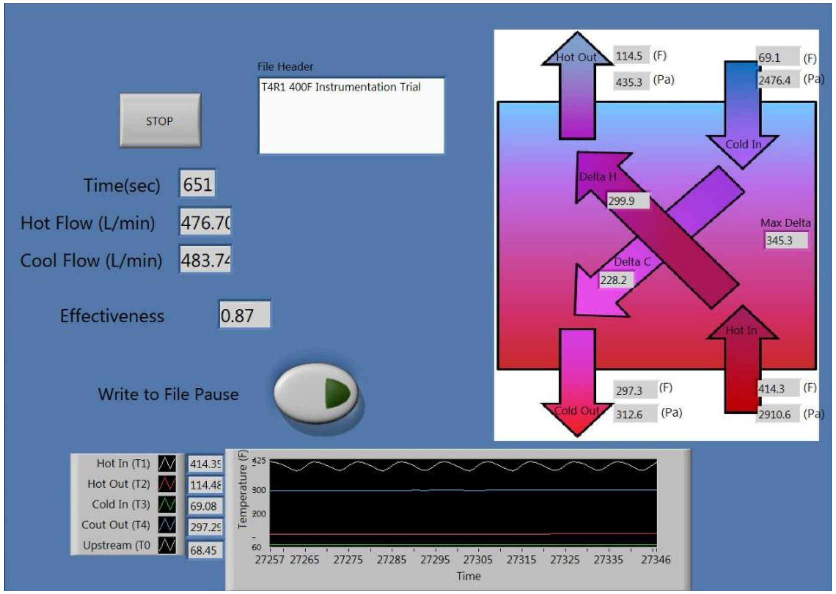
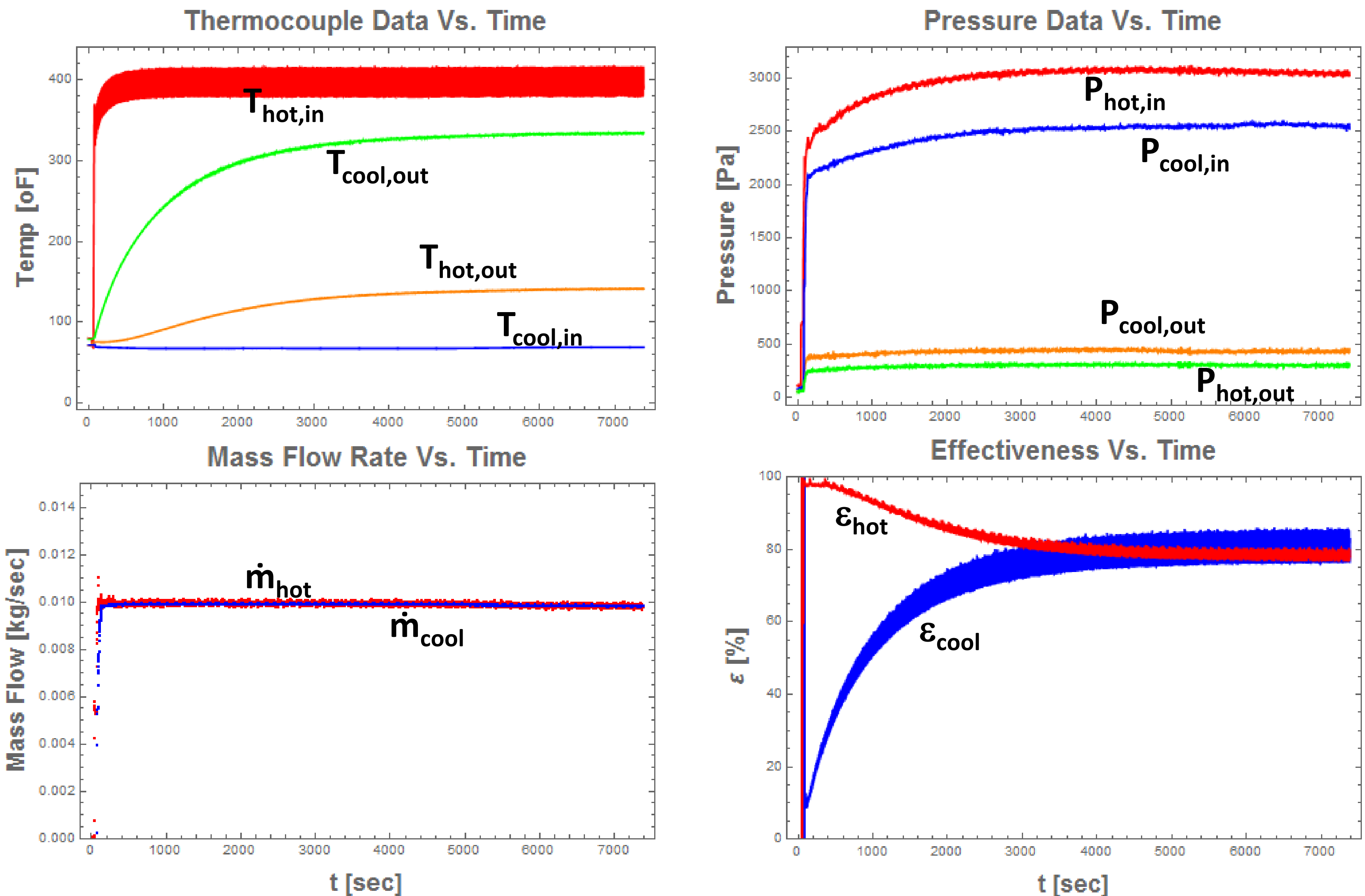


Effectiveness and Pressure Drop Tests

PROTOTYPE PERFORMANCE TESTING

Testing: Typical Raw Data



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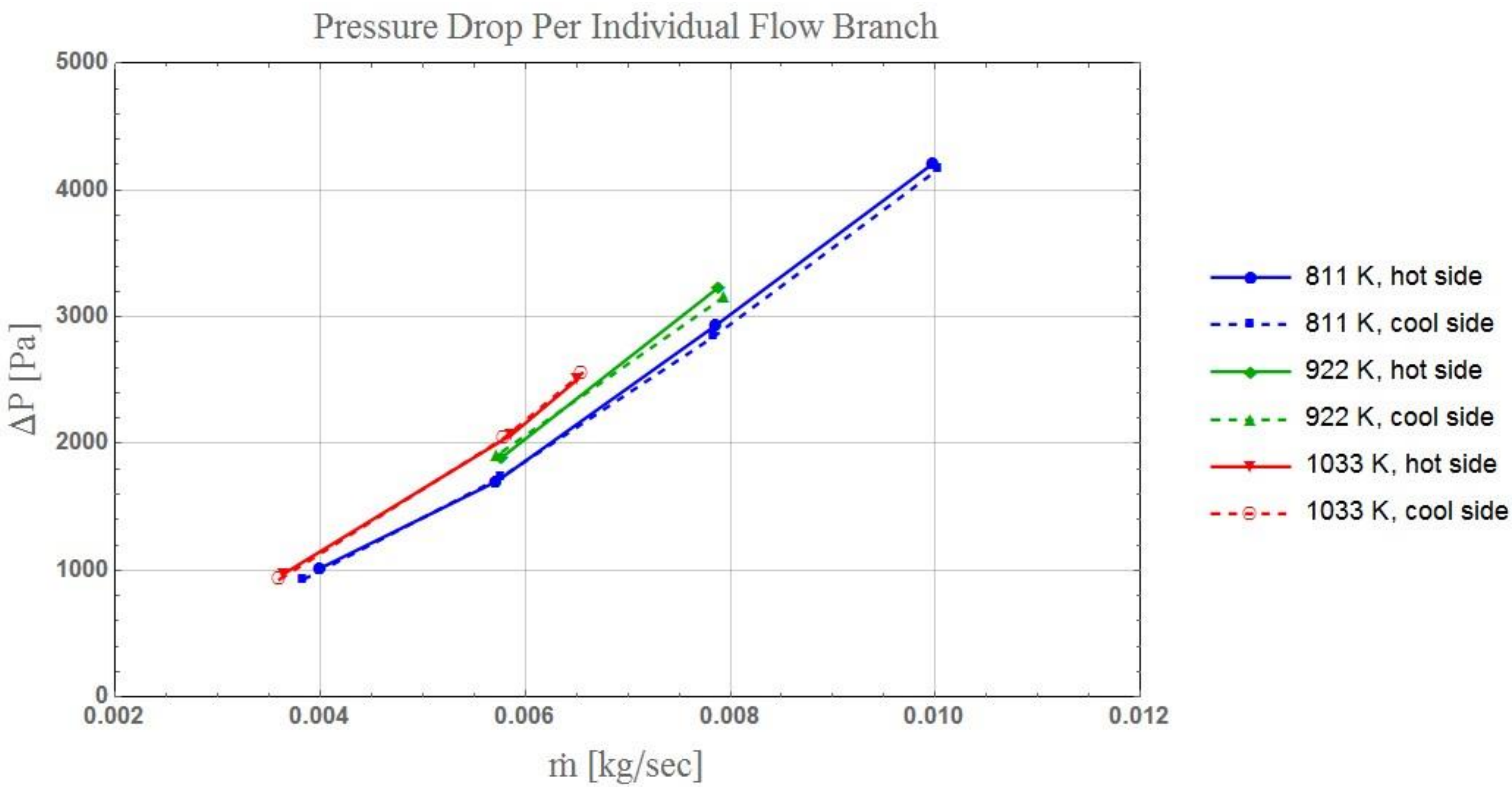
Pressure Drop vs. Mass Flow



Total ΔP at operating condition is about 6 kPa (0.87 psi), outside of design target…

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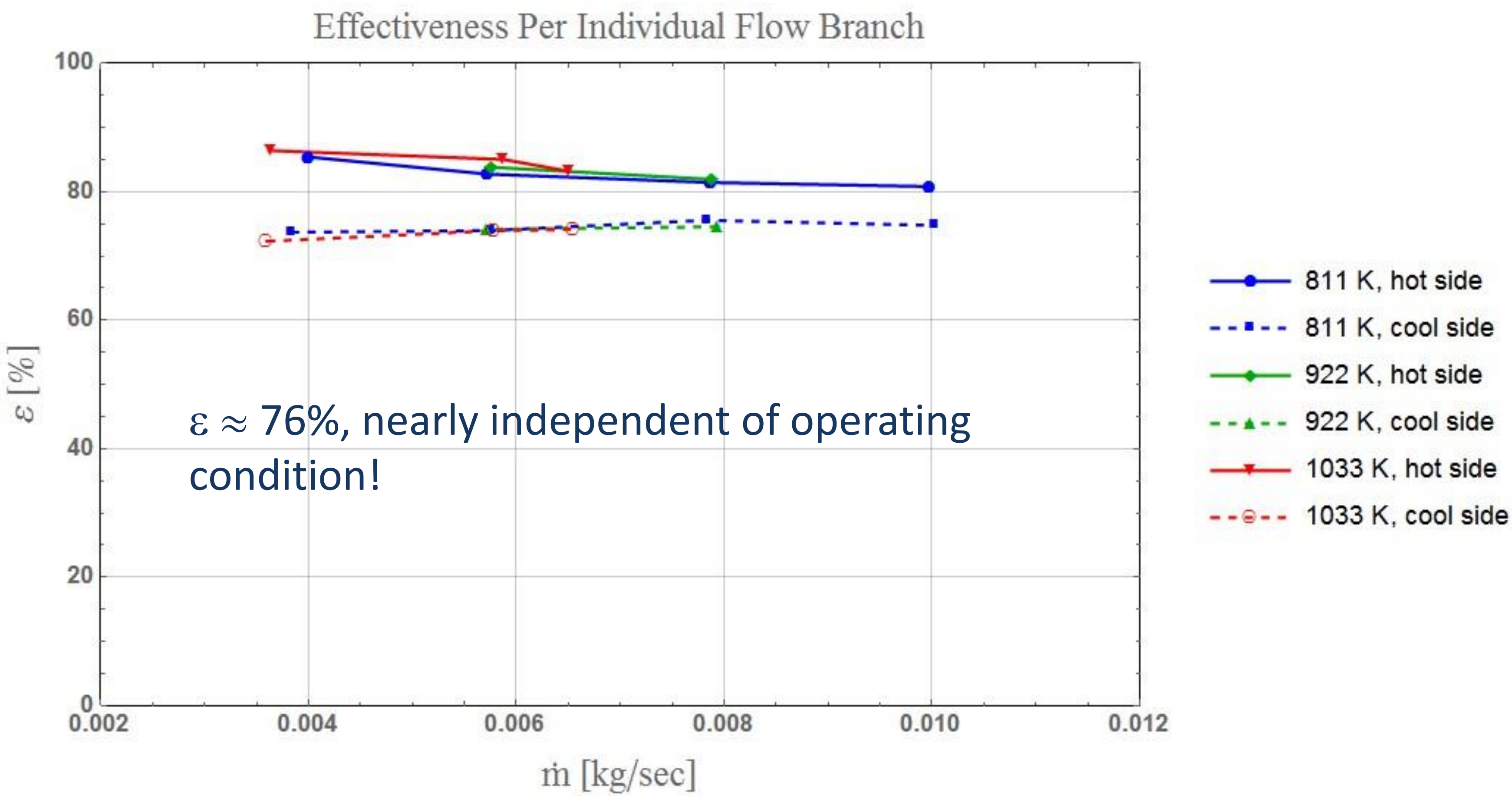
Effectiveness vs. Mass Flow



$\varepsilon \approx 76\%$, nearly independent of operating condition!

Difference between hot and cool side values is due to losses to ambient, which make the hot-side flow lose more heat than it would if it were transferring heat only to the cool side. The cool-side values are more realistic.

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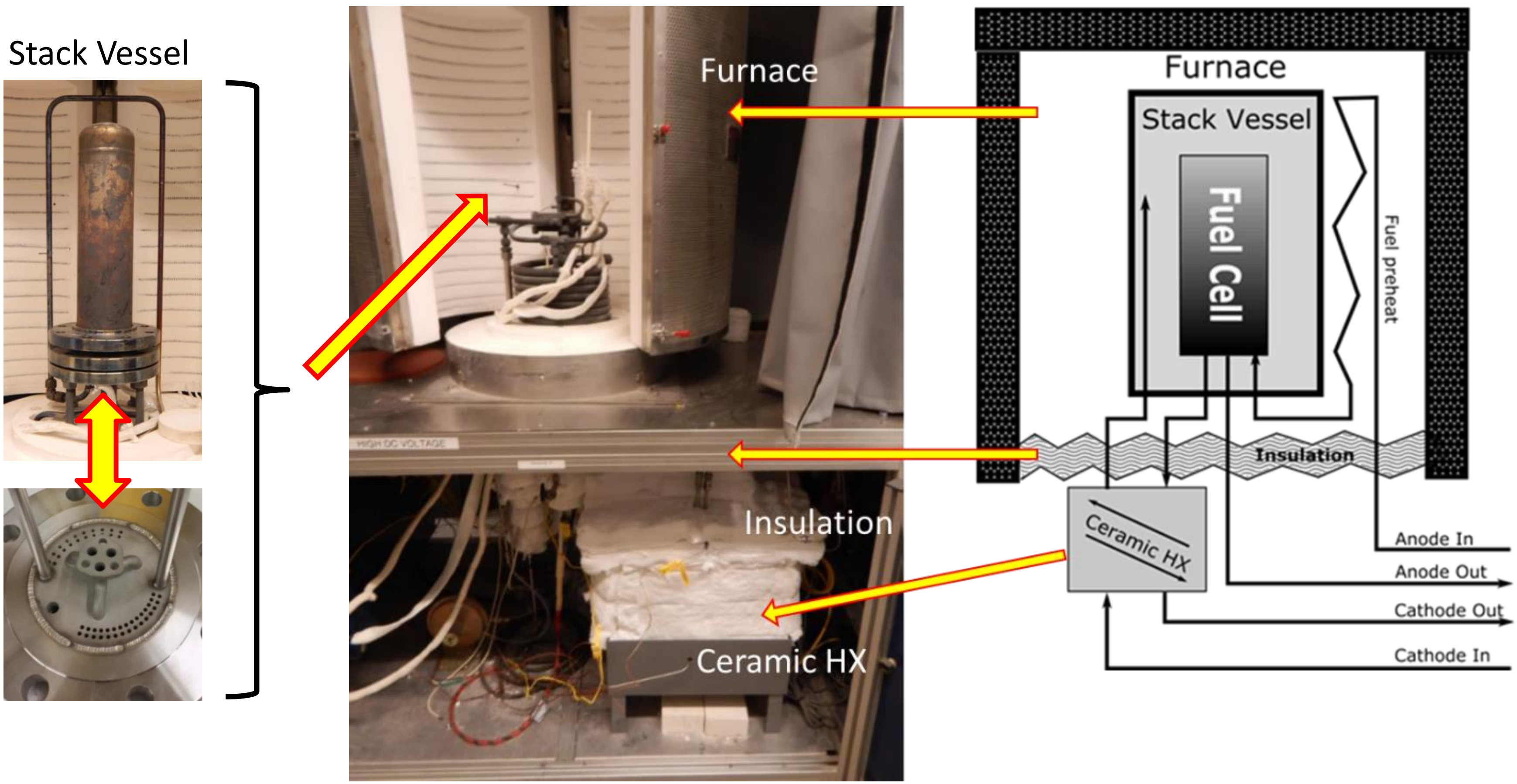
Integration to Fuel Cell Test Stand



Closing Remarks

- Successfully Designed and Prototyped Ceramic Heat Exchanger for Fuel Cell Application
  - Modular Design Allows Great Flexibility for Application-Specific Performance Matching
- Installed Heat Exchanger into Fuel Cell Test Stand
- Immediate Next Steps:
  - FCE data collection with fuel cell
- Future Steps
  - Simplify Manufacturability

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- The authors particularly acknowledge the support of Dr. Sydni Credle, at the Crosscutting Research Division, National Energy Technology Laboratory (NETL).
- We also acknowledge the technical advice provided by Dr. Hossein Ghezel-Ayagh and his team at Fuel Cell Energy, Inc.

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Questions and Discussion

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