Novel Compact Ceramic Heat Exchanger For Solid Oxide Fuel Cell Cathode Air Preheater Application

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Crosscutting Research Division

National Energy Technology Laboratory (NETL)

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MiTi: What We Do

ORC Turbogenerator

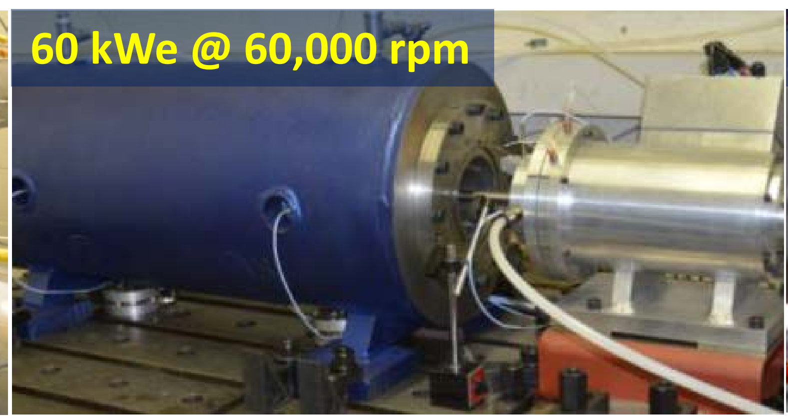
Air Cycle Machine

Hydrogen Blower

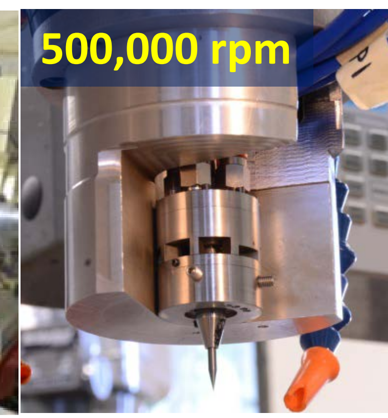
Fuel Cell Compressor

Hydrogen Pipeline Compressor

Flywheel Electromechanical Battery



Micro Machining



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

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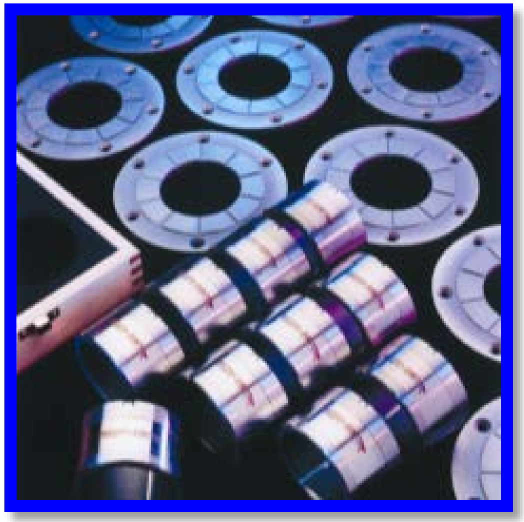
At the Core: MiTi's Advanced Foil Bearings





- **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 810°C (1500°F)**
- **Negligible Friction Power Loss ⇔ High Mechanical Efficiency**

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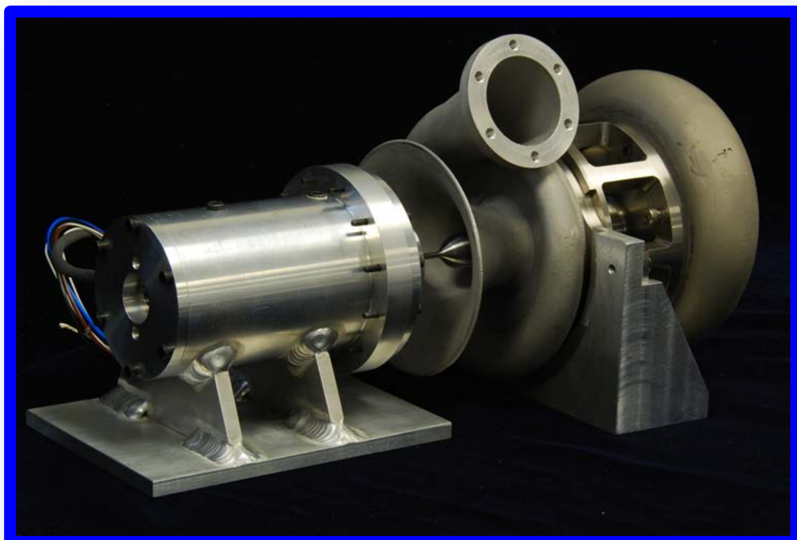
Background

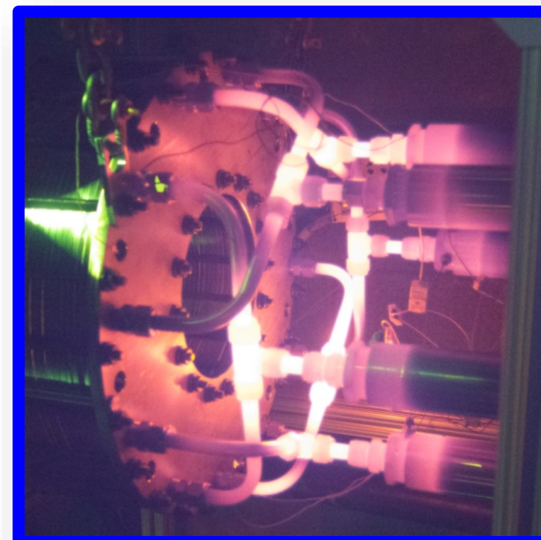
MiTi® 8 kW Turboalternator

- 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: ε ☐0.9
- Radial geometry fits around combustor
- Increase in Thermal Efficiency 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

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Project Team

MiTi

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

FuelCell Energy, Inc.

- Hossein Ghezel-Ayagh, Ph.D.
  - FCE Lead
- Robert Sanderson, P.E.
  - Systems 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)

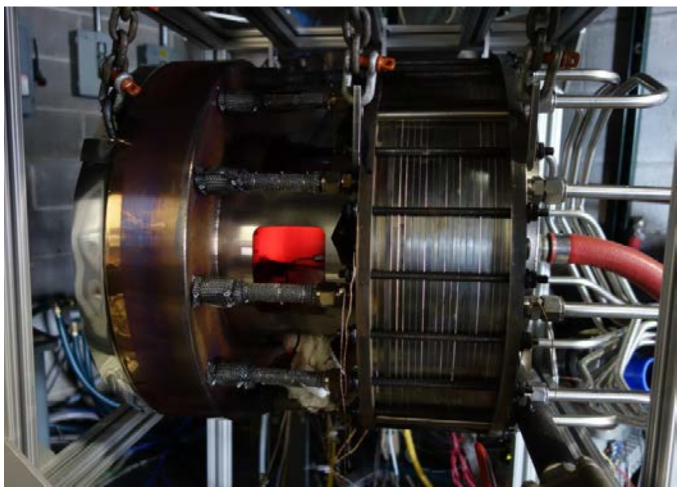
Motivation for Use of Ceramics

- 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 required low pressure drop (3 to 5 psi)



  - Attained around 90% heat transfer effectiveness at engine operating conditions.

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

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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/Test of Subscale Heat Exchanger Elements
5. Fabrication/Test of Heat Exchanger Prototype

Target Application: Solid Oxide Fuel Cell Operating Conditions

IDENTIFICATION OF SOFC REQUIREMENTS

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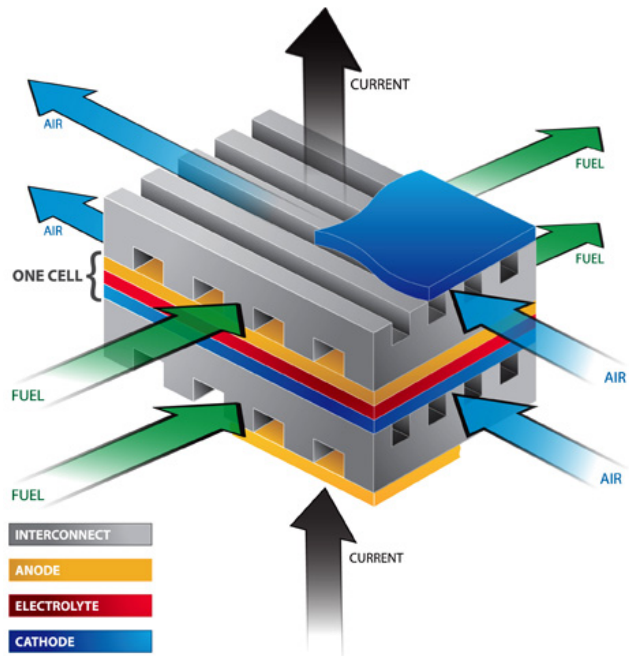
Target Application

- FuelCell Energy Inc.
  - Proof Of Concept 50 kW_e SOFC

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power



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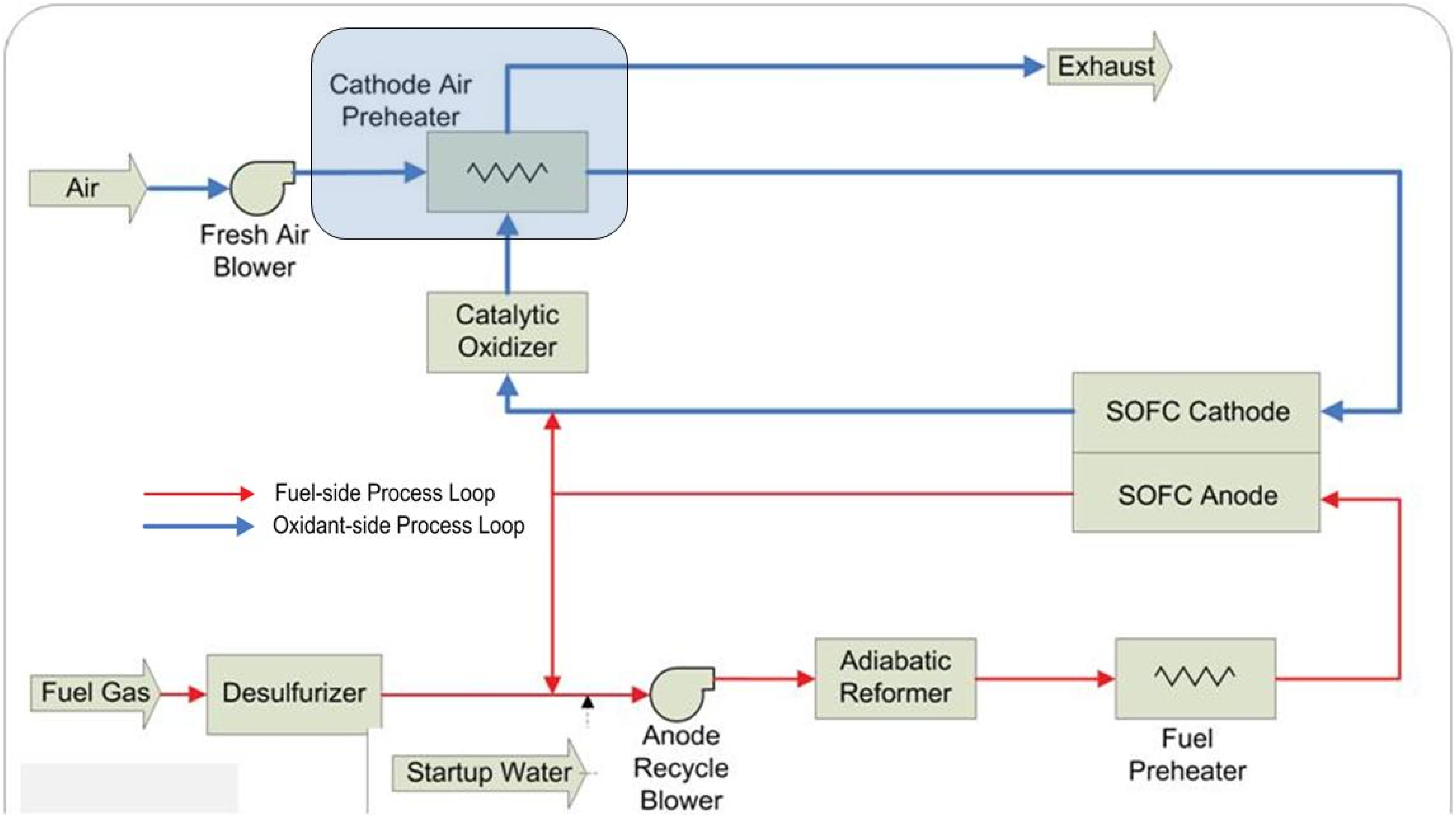
SOFC System Schematic



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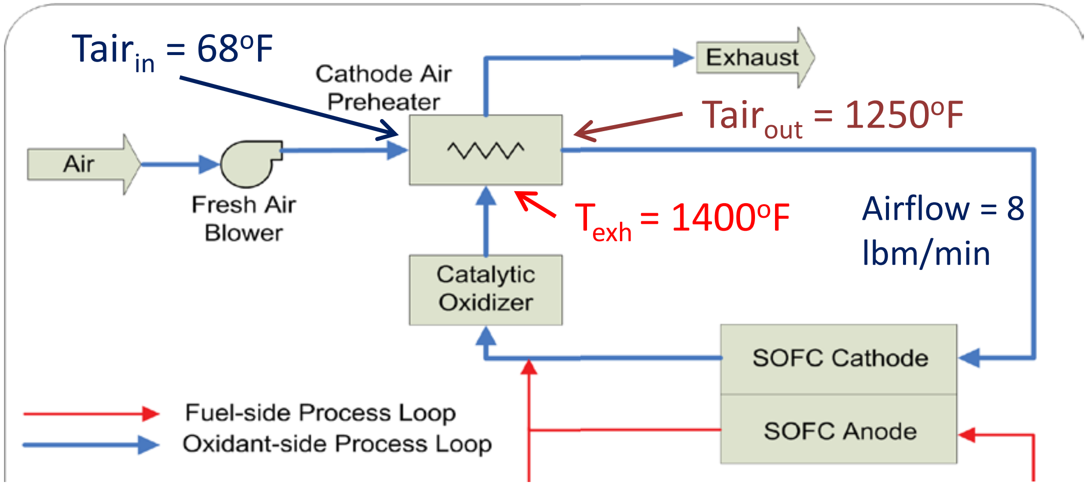
Cathode Air Preheater Requirements

- Preheater Operating Conditions:



- Required Preheater Heat Transfer:

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

- Total Allowable Pressure Drop: $\square P_{tot} = 0.5$ psi

Heat Transfer Analysis and Heat Exchanger Sizing

MiTi'S RECUPERATOR EXPERIENCE

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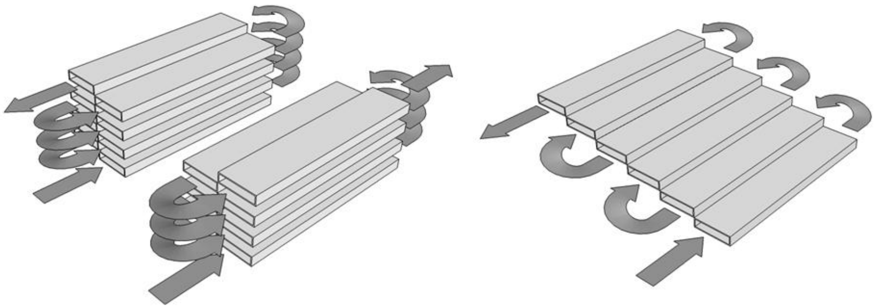
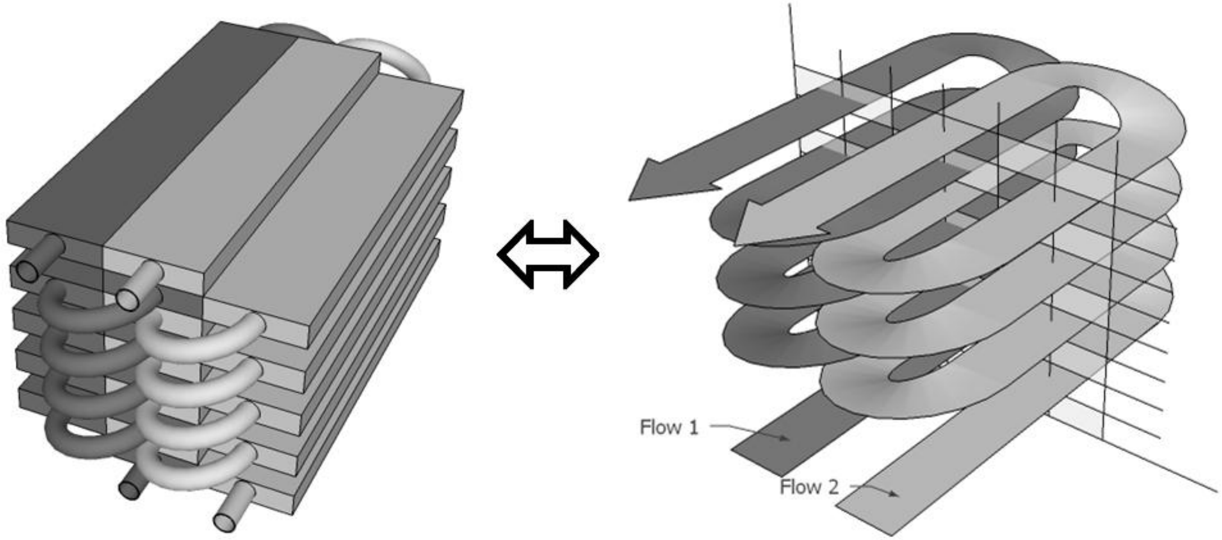
MiTi's Recuperator Experience

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





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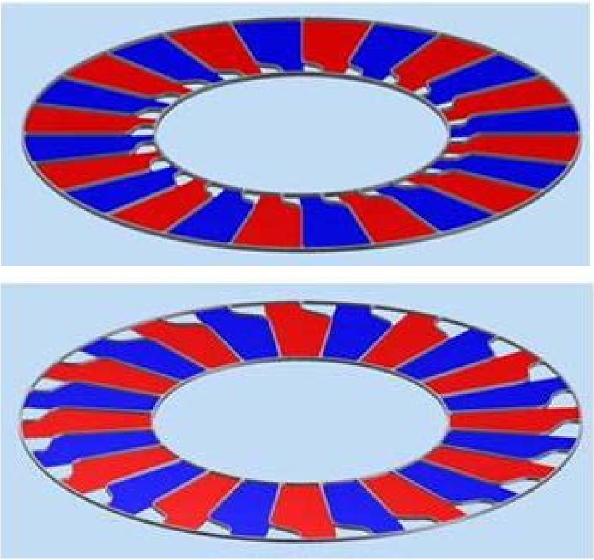
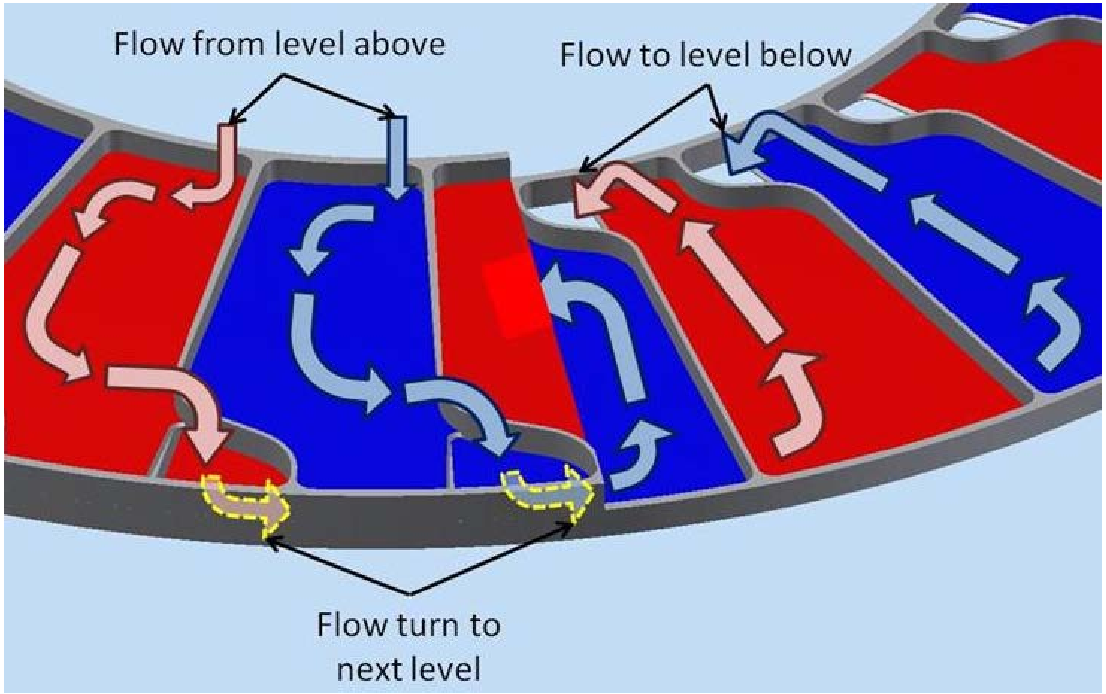
Patent Pending Design

- 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





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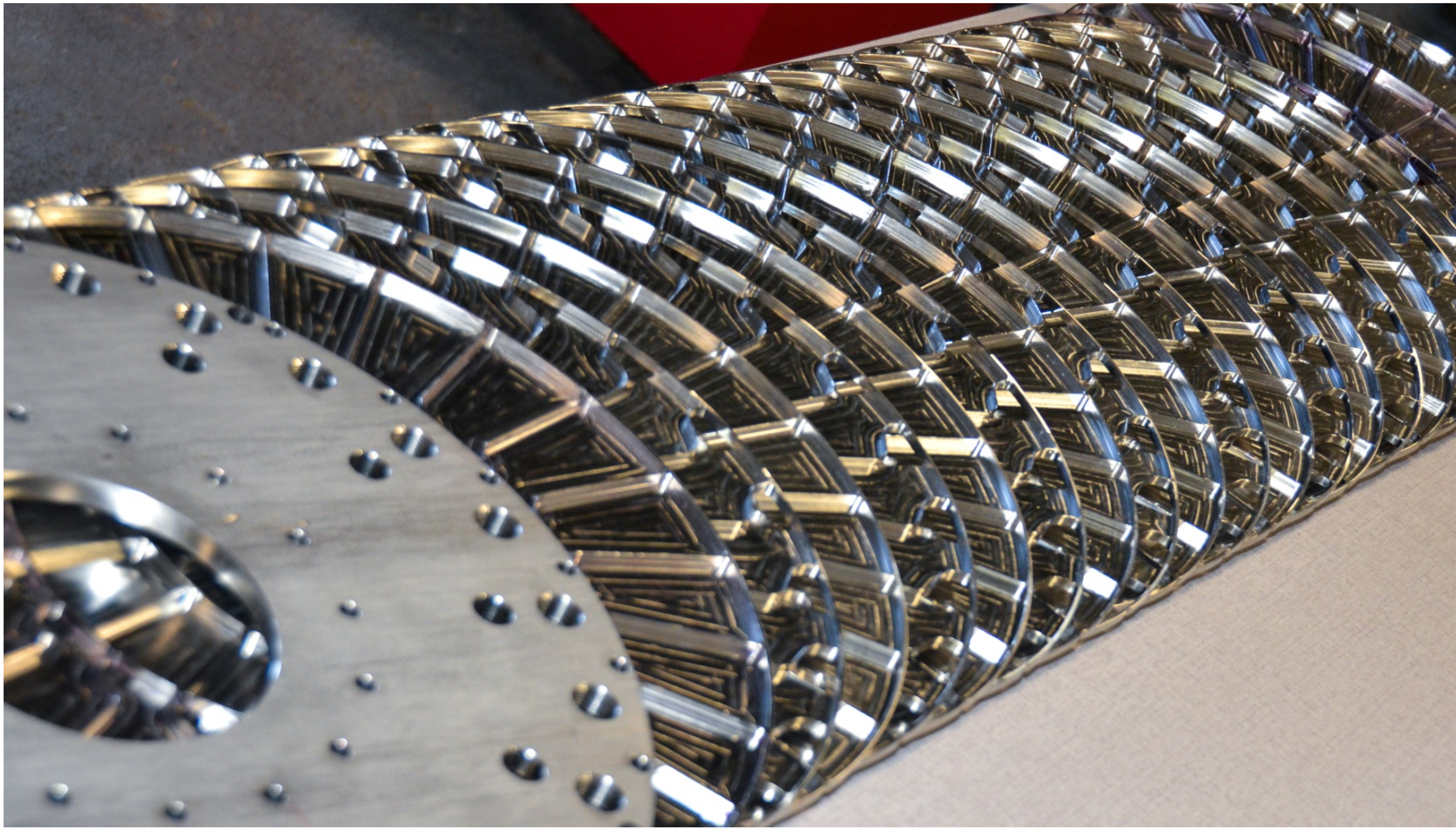
CNC-Machined Heat Transfer Elements



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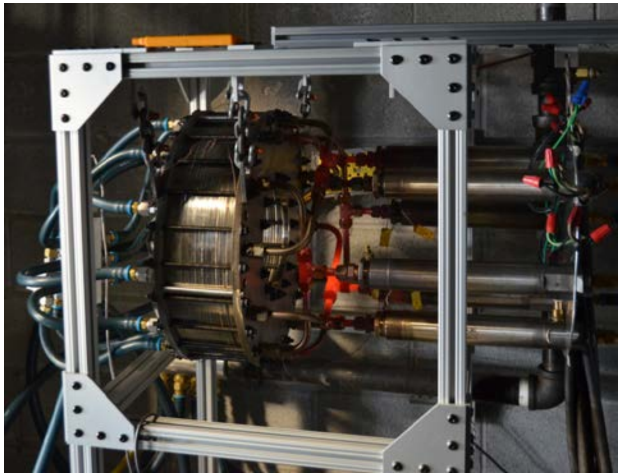
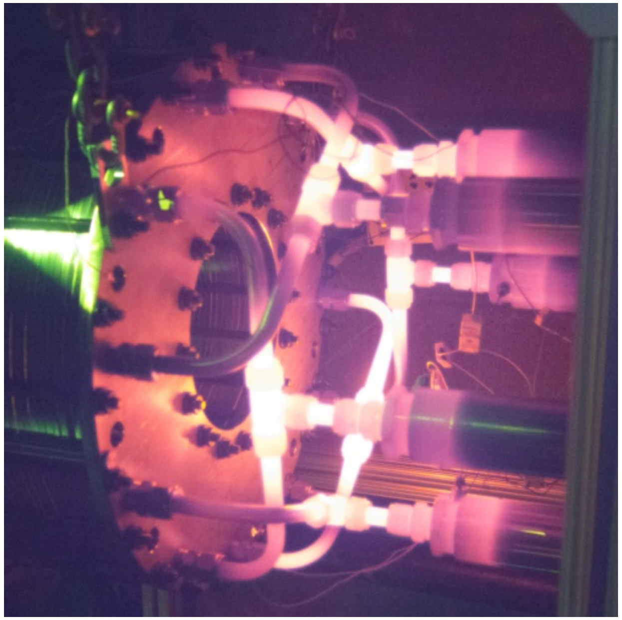
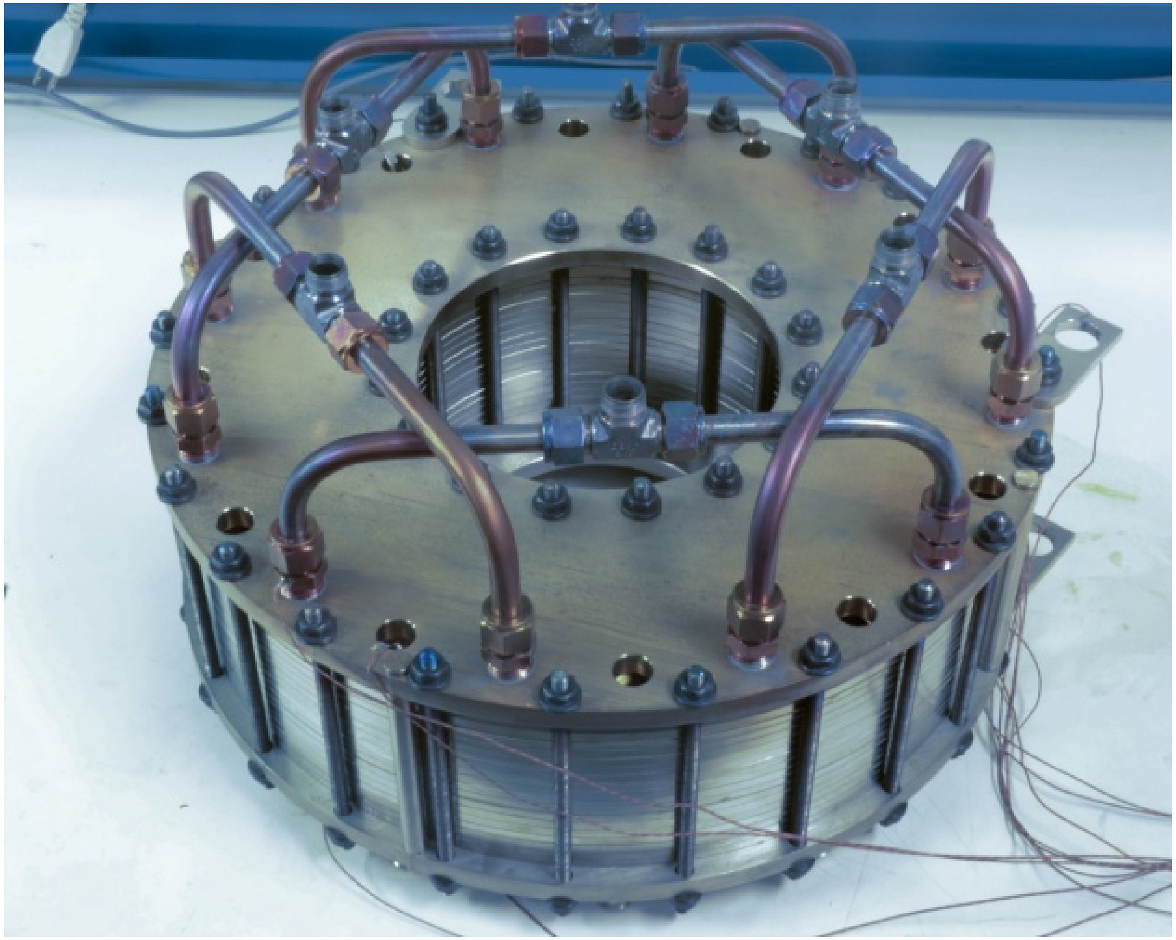
Recuperator Testing







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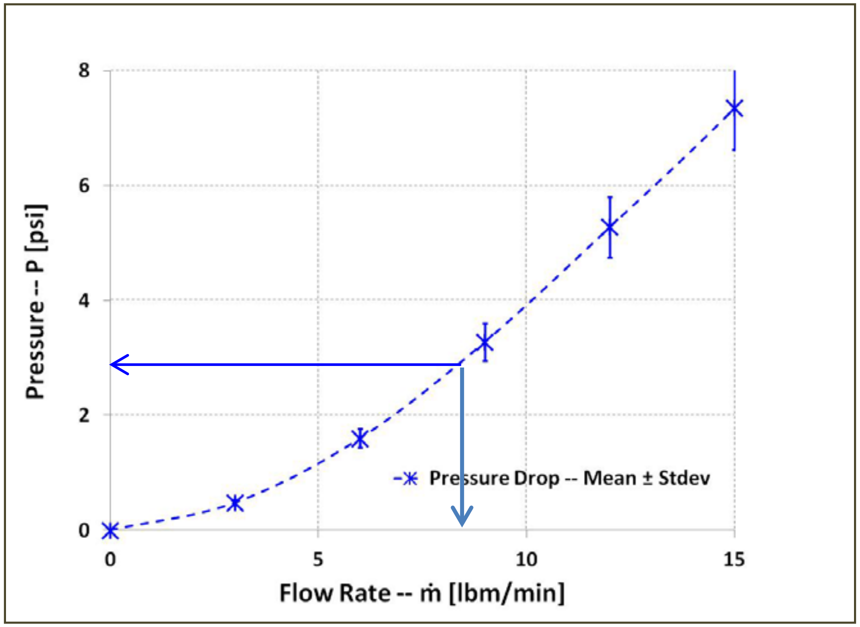
Experimental □P vs. ṁ Performance

- Pressure drop designed to satisfy engine constraints.
  - Turbine design pressure drop too high for fuel cell
- SOFC imposes no weight or size limit constraint □ Pressure drop can be designed to be significantly lower.



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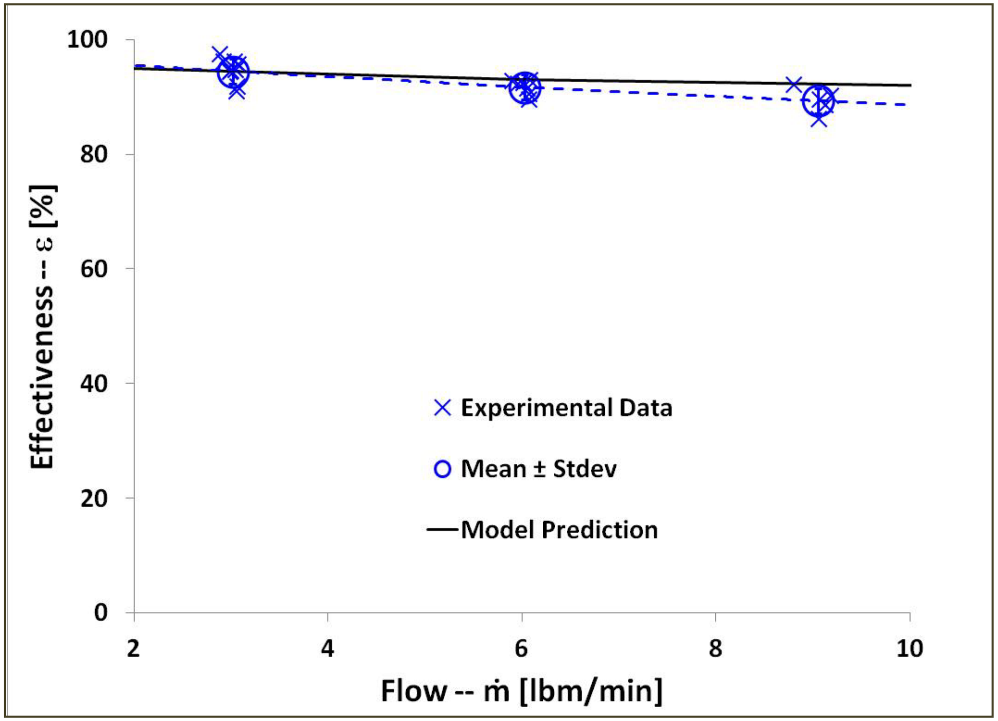
Experimental Effectiveness Performance

- Measured effectiveness is uniformly high over range of operating flows.
- Theoretical model fully validated □High confidence in tool for sizing of SOFC heater



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Heat Transfer Analysis and Heat Exchanger Sizing

HEAT EXCHANGER DESIGN

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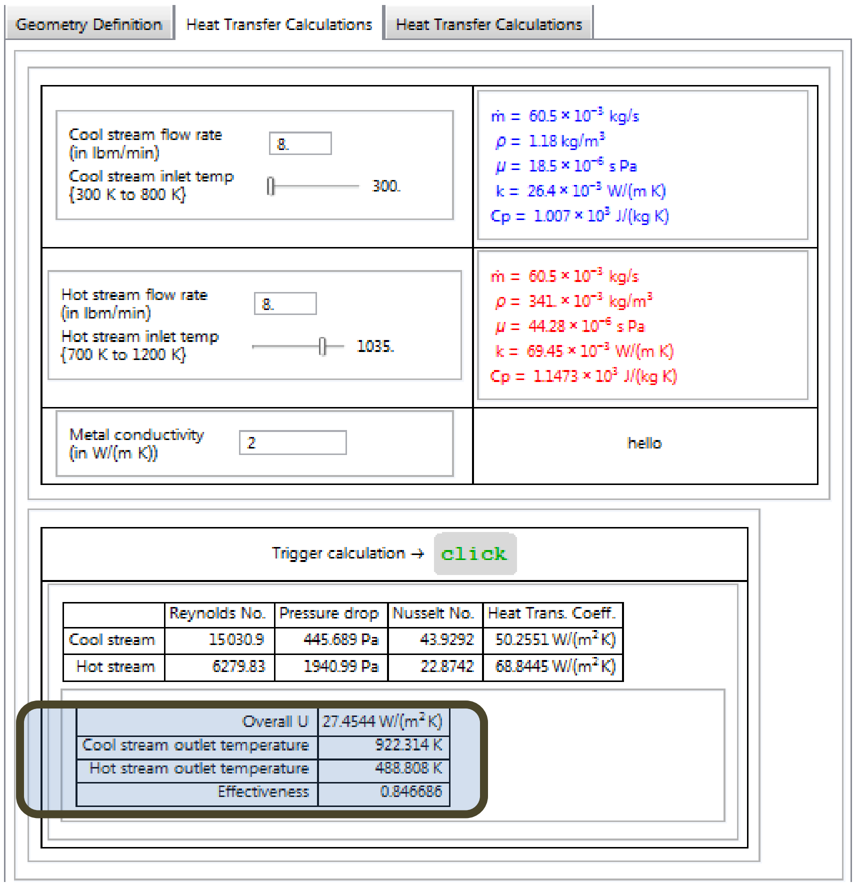
Preliminary Heat Exchanger Design

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

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



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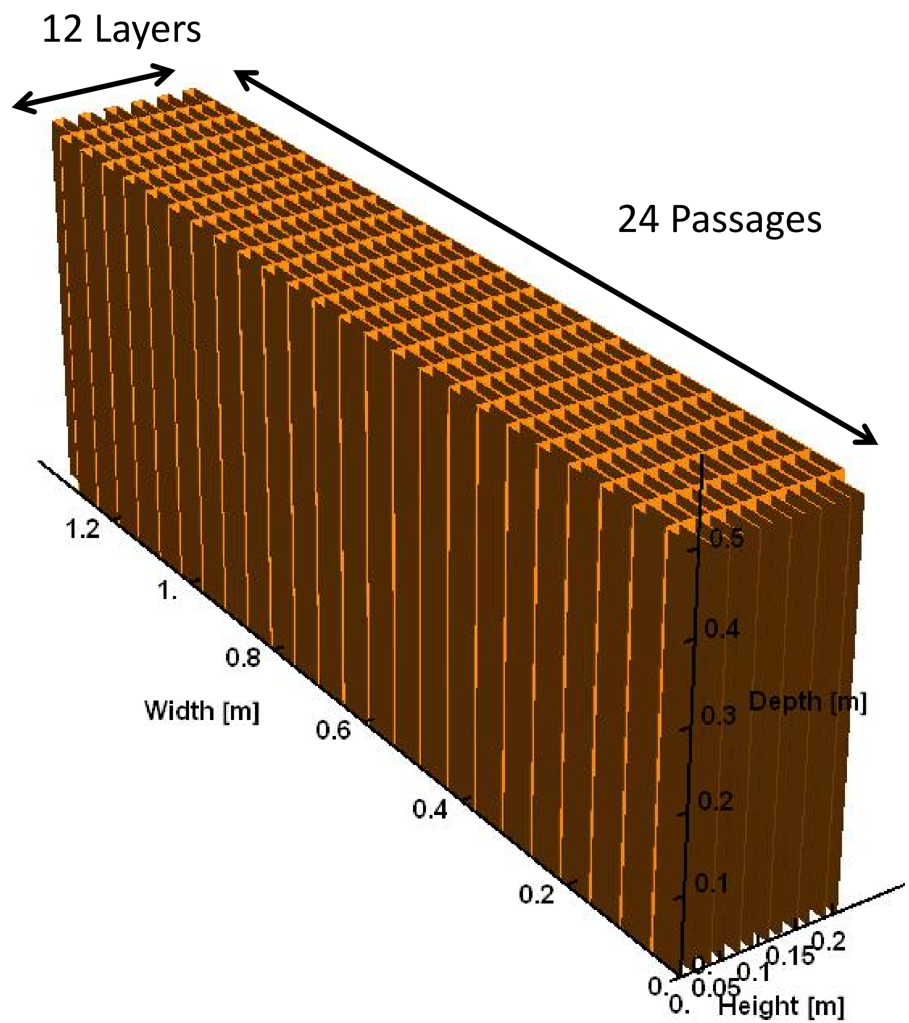
Preliminary Heat Exchanger Design

- 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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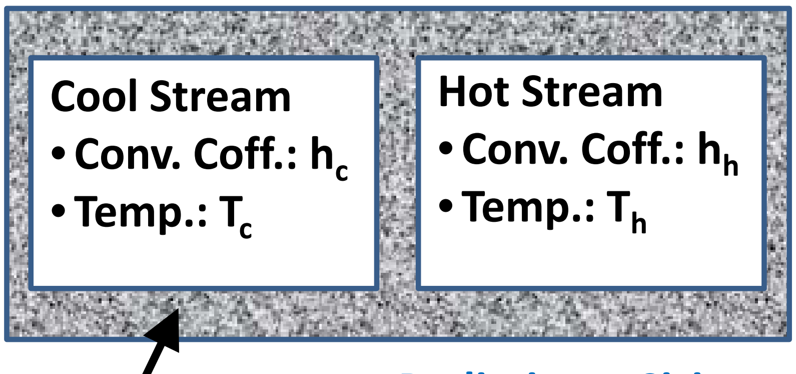
Parametric Study For Design Optimization

Basic Heat Transfer Element



Walls:
- Thickness: L
- Conductivity: k

Preliminary Sizing:

	Heat Trans. Coeff.
Cool stream	50.2551 W/(m² K)
Hot stream	68.8445 W/(m² K)

Heat transfer between flows:

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

Overall Heat Transfer Coeff.:

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

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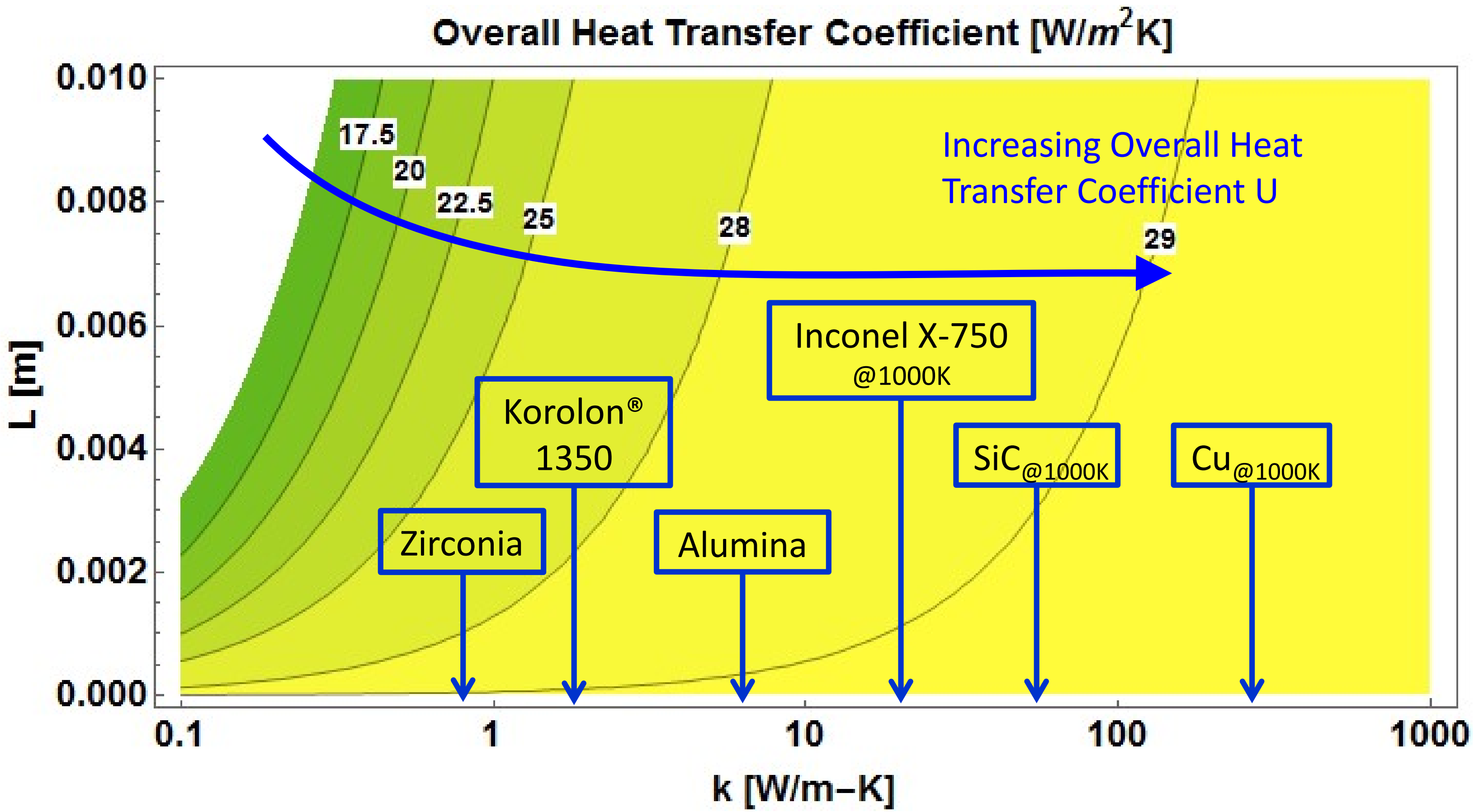
Effect of Wall Thermal Conductivity

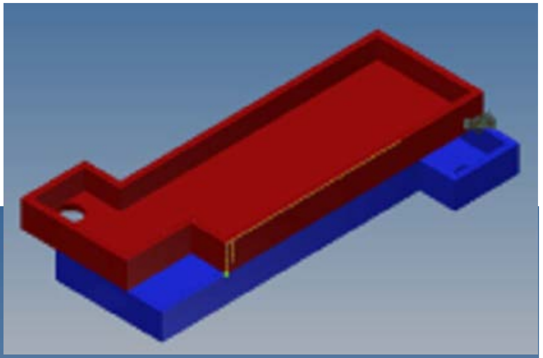


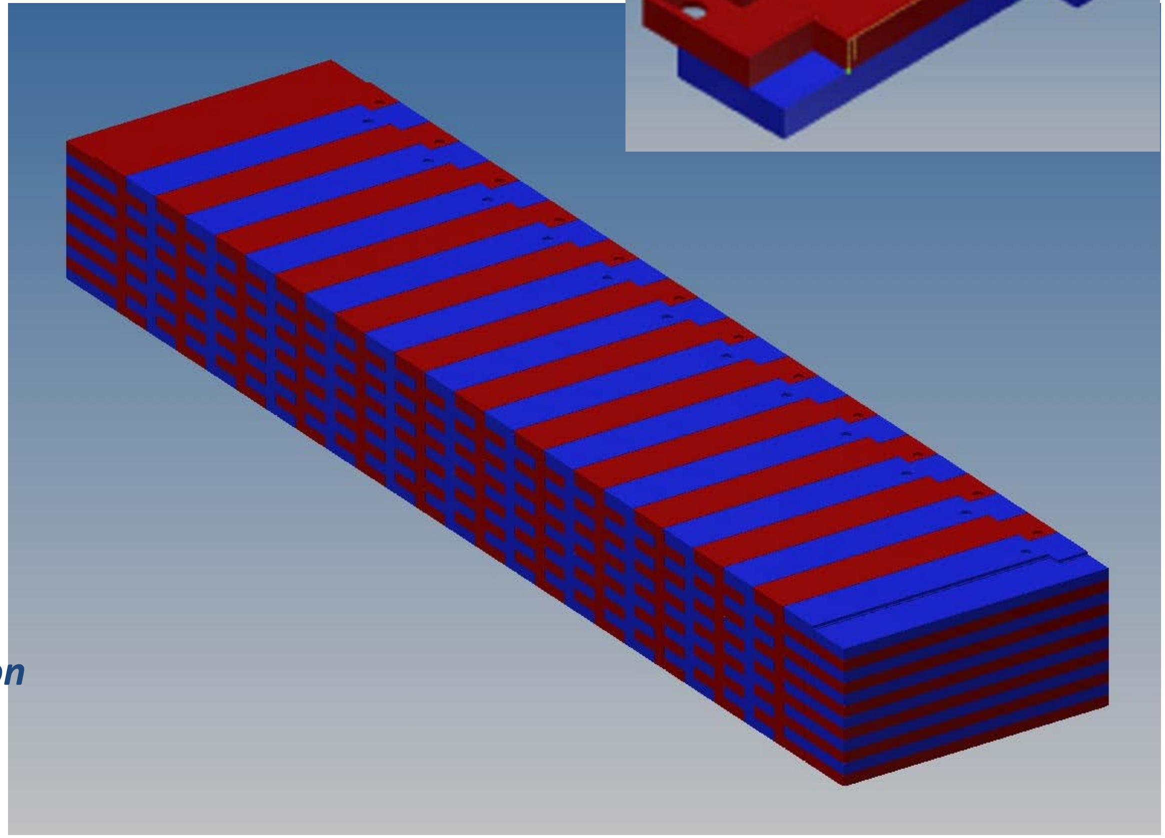
At SOFC operating conditions and practical wall thickness (L < 0.005 m), the walls are thermally thin, and the overall heat transfer coefficient is nearly *independent of wall conductivity,* therefore, the choice of material is irrelevant.

Heat Exchanger Preliminary Layout

- Modular segments form overlapping quasi-helical flow paths.
- Design allows to add or remove segments according to flow, pressure drop, or heat exchange rate requirements.

- ***Patent Pending: U.S. Provisional Patent Application US62/040,559***





Material and Fabrication Considerations

FABRICATION TRIALS

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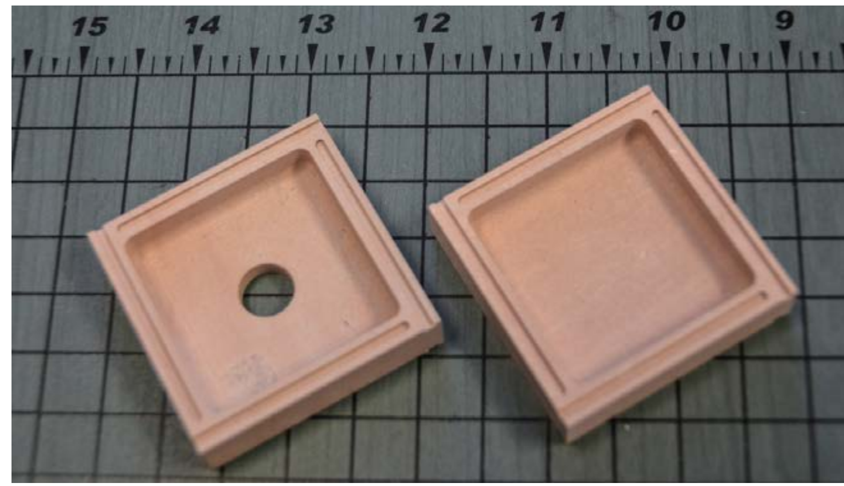
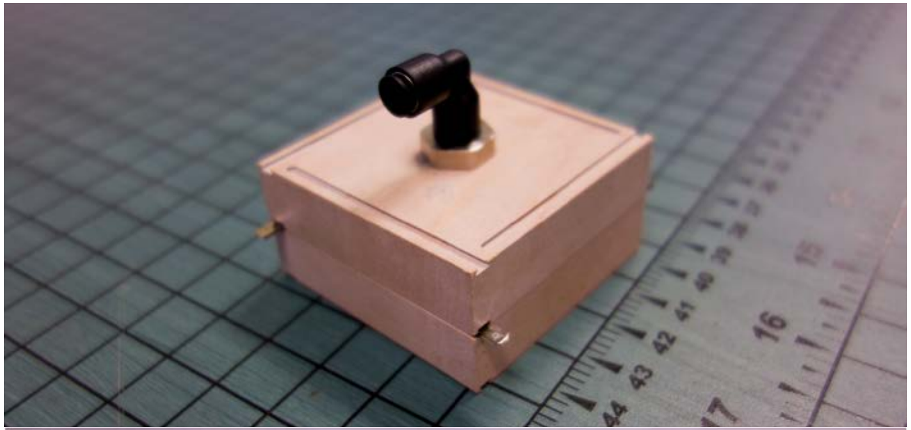
Component Fabrication Testing

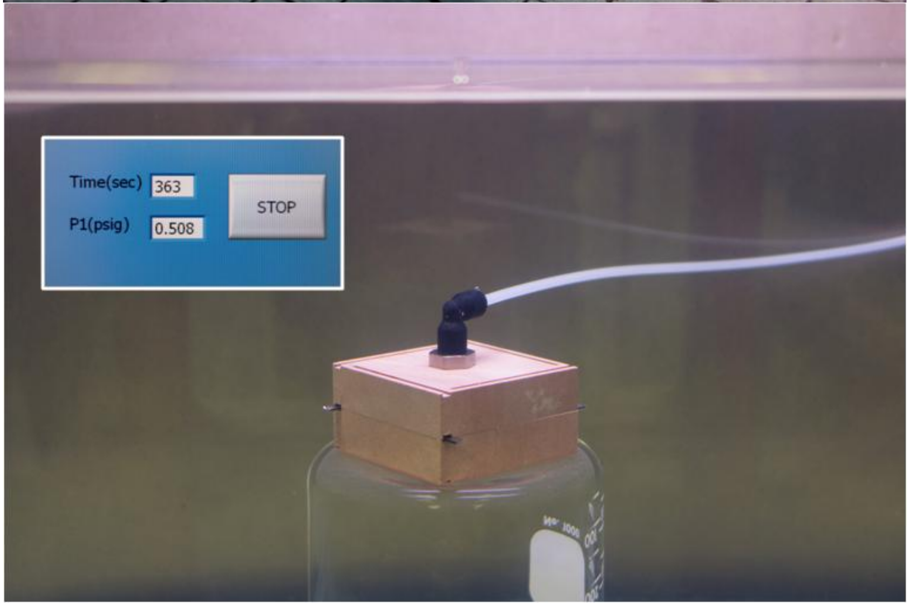
- Material Selected: Alumina-Silicate Machinable Ceramic
  - Machined in Green State
  - Partially Fired to 1600^{o}F
- Geometric Tolerance □1%



Seal Pressure/Leak Tests

- Successfully Held 0.5 psi
- Total Allowable Drop over Device: 0.33 psi, or less than 0.03 psi per Passage Segment (Assuming each Passage is Made from 10 Segments) ⇔ Huge Pressure Margin





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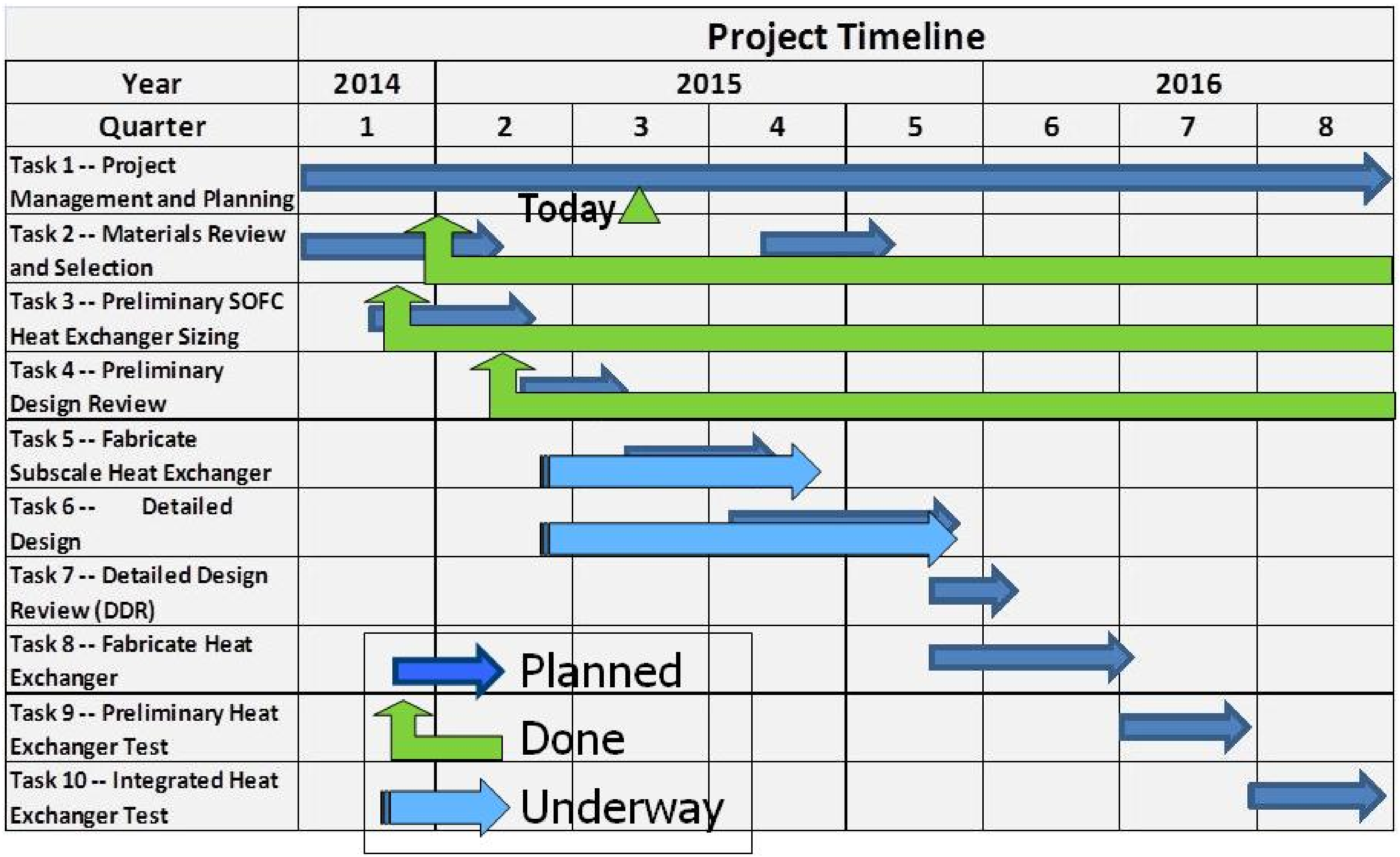
Closing Remarks

- Status: Program Well Underway
  - Identified SOFC Preheater Requirements
  - Preliminary Preheater Design Established
  - Materials Selection Done
  - Prototype Fabrication Trials Underway

- Next Steps
  - Define/Design Interface to SOFC
  - Performance Tests on Subscale Device
  - Integrate Prototype
    - Long Duration Testing
      - 1000 Hours on SOFC
    - Post-Test Inspection

Program Schedule



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Questions and Discussion

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