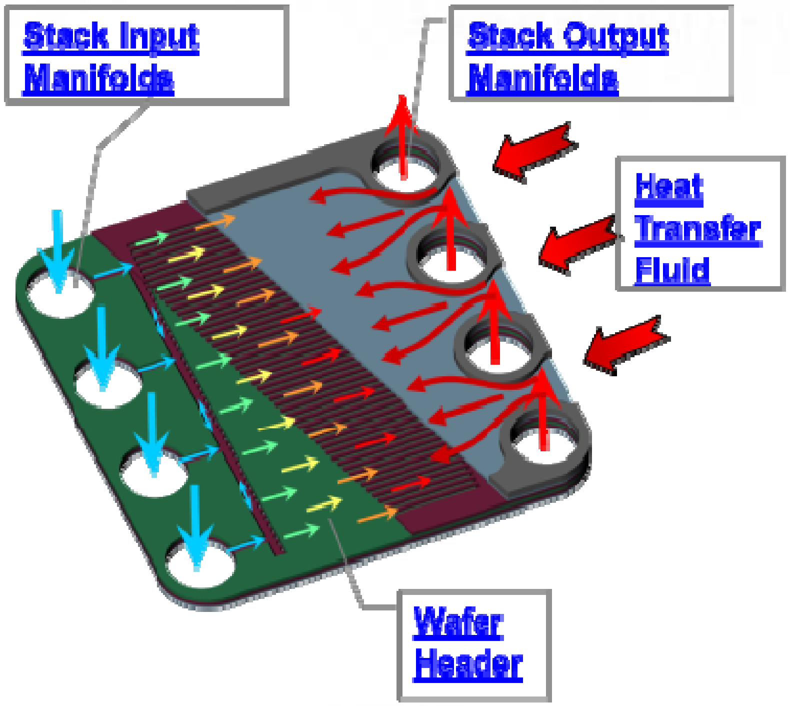
Compact, Ceramic, Microchannel Heat Exchangers



C. Lewinsohn and J. Fellows - Ceramatec, Inc.

N. Sullivan, R.J. Kee, and R. Braun – The Colorado School of Mines

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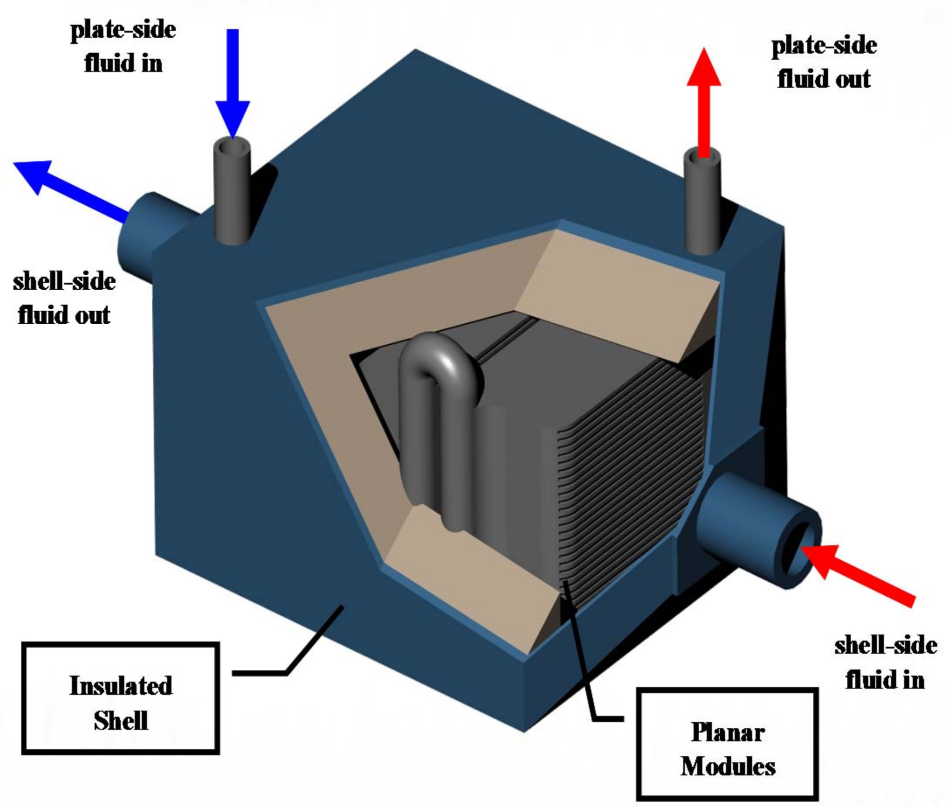
Introduction & Overview

- Benefits/Objectives
- Design Modeling
- Fabrication
- Testing
- Summary



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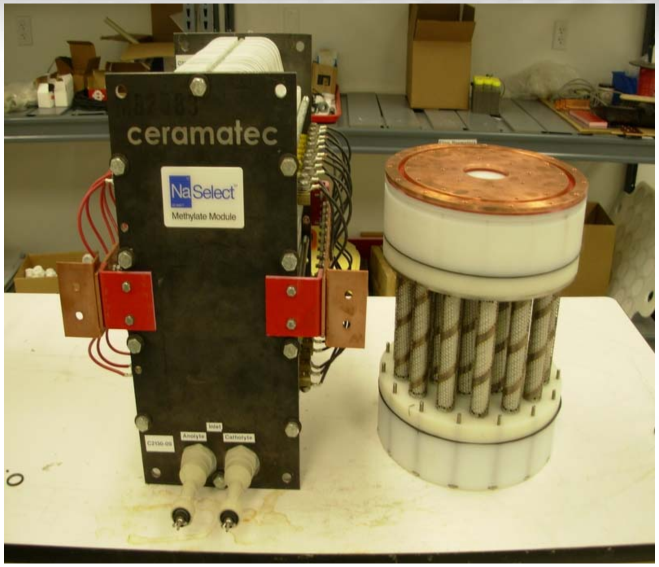
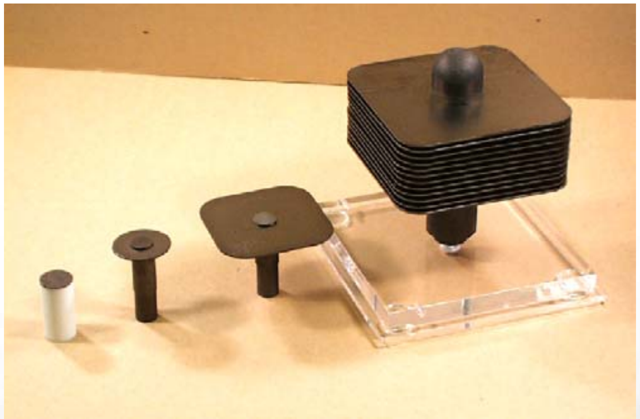
Ceramatec Overview

- **Founded 1976**
- **Owned by CoorsTek, LLC**
  - **Global manufacturer of technical ceramics.**
- **8,000 m^2 R&D and Mfg Facility**
- **Concept to commercialization**
  - **R&D --> prototype --> pilot scale --> fabrication**
- **Core competencies:**
  - **electrochemistry, ionic conducting ceramics, microchannel components, & advanced materials**
- **Customers**
  - **40% Fortune 500 companies**
  - **60% Govt. R&D**





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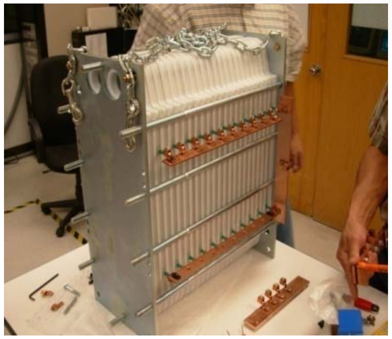
Ceramatec: Business Models

Labscale Concept Development

Self & Government Funded

Benchscale Multi-Cell

Corporate/ Partner Funded



Prototype Unit

Commercial Unit

Manufacturing
Joint Venture
Licensing
Spin Off Company

SELECTION TECHNOLOGIES™

Integrated electrochemical systems utilizing ionic transport membrane technology

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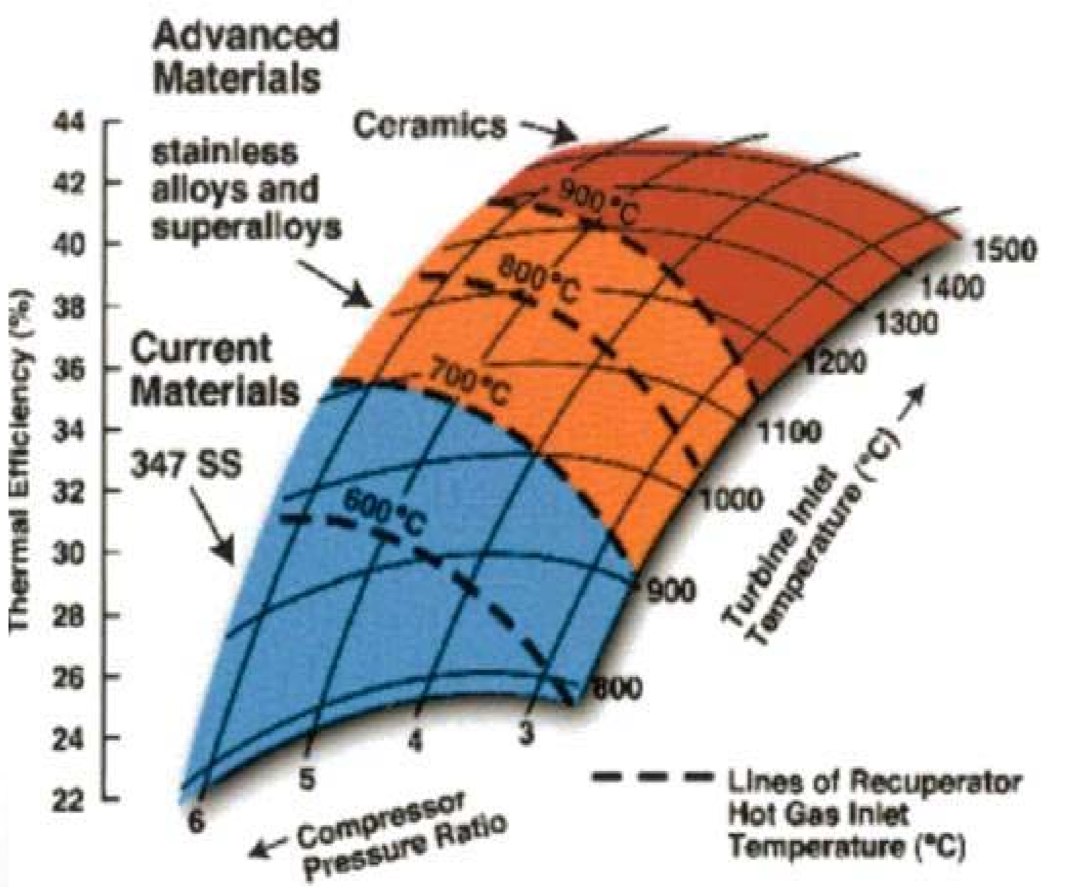
Benefits of Ceramic Heat Exchangers

- Allow higher operating temperatures.
  - Higher efficiency
  - Reduced emissions
- Corrosion resistant
- Low cost



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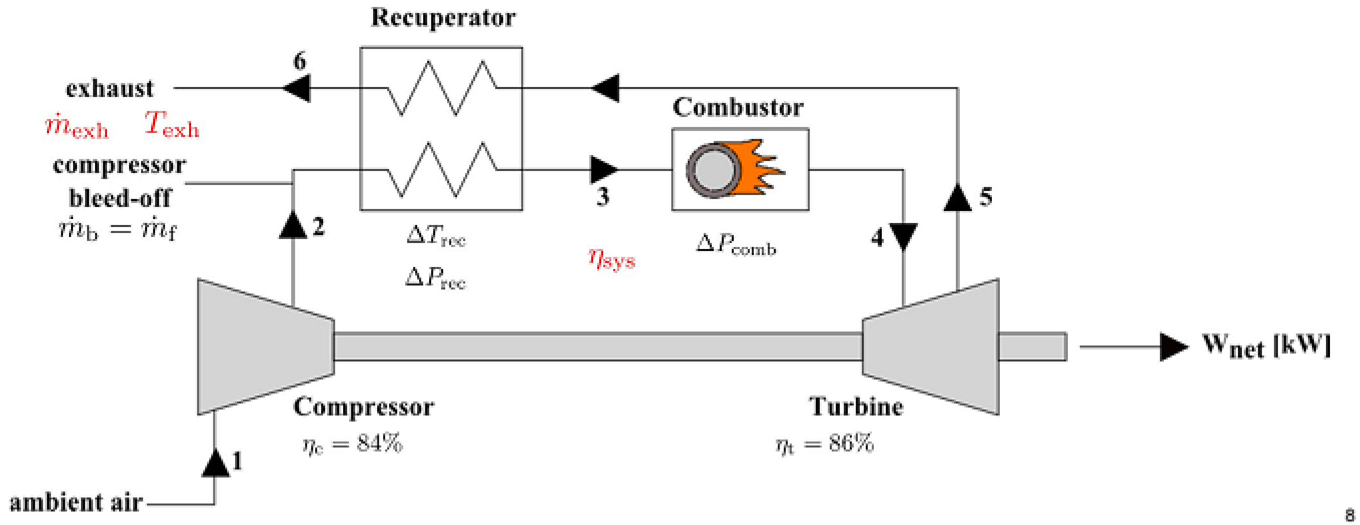
Project Objectives

- Validate design tools for ceramic, microchannel heat exchangers.
- Demonstrate commercial manufacturing methods.
- Demonstrate integration of ceramic components with hot flow manifolds.
- Demonstrate thermal performance of high-temperature heat exchangers.
- Advance technology from labscale to benchscale.

Project Tasks

- ✓ Task 1: Project Management
- ✓ Task 2: Heat Exchanger Plate Design and Analysis
- ✓ Task 3: Heat Exchanger Plate Fabrication and Testing
- Task 4: Prototype Stack Fabrication
- Task 5: Prototype Stack Testing

System Modeling - Microturbine



Turbine Model and Net Power (kW)	C30	C65	C200
Pressure Drop (kPa)	10	7.5	7.5
Air Side Mass Flow Rate (kg/s)	0.2991	0.498	1.348
Exhaust Side Mass Flow Rate (kg/s)	0.3051	0.5027	1.36
Air Inlet (SP 2) Temp (C)	149.4	168.1	190.6
Air Outlet (SP 3) Temp (C)	589.4	571.6	594.7
Exhaust Inlet (SP 5) Temp (C)	694.4	690.6	666.7
Exhaust Outlet (SP 6)Temp (C)	275.3	309.3	280.7
Recuperator Heat Transfer (kW)	140.9	215.2	585.8
Recuperator Effectiveness	0.799	0.7632	0.8427

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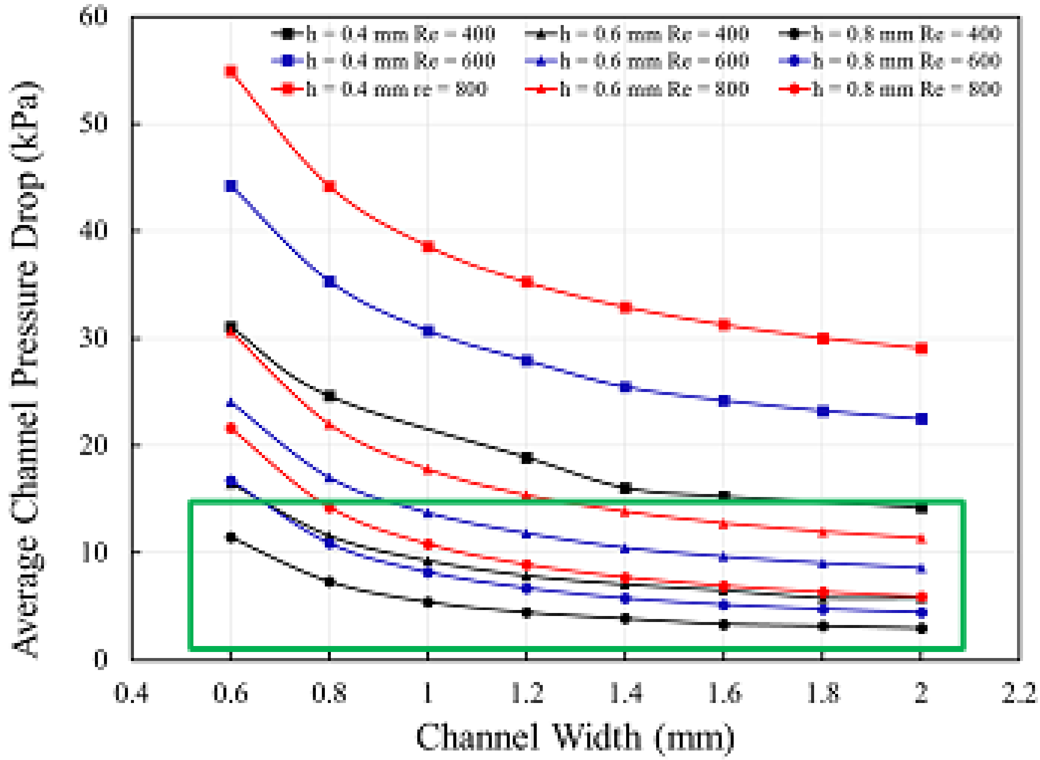
Microchannel Modeling – Pressure Drop



- Channel height ≥ 0.6 mm
- Low Reynolds number required for narrow channels

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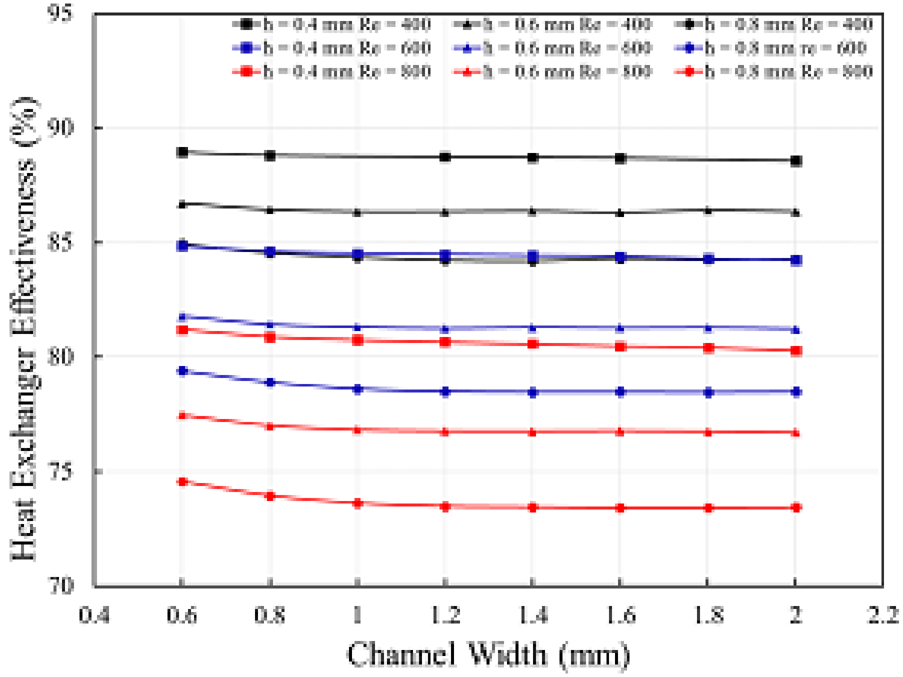
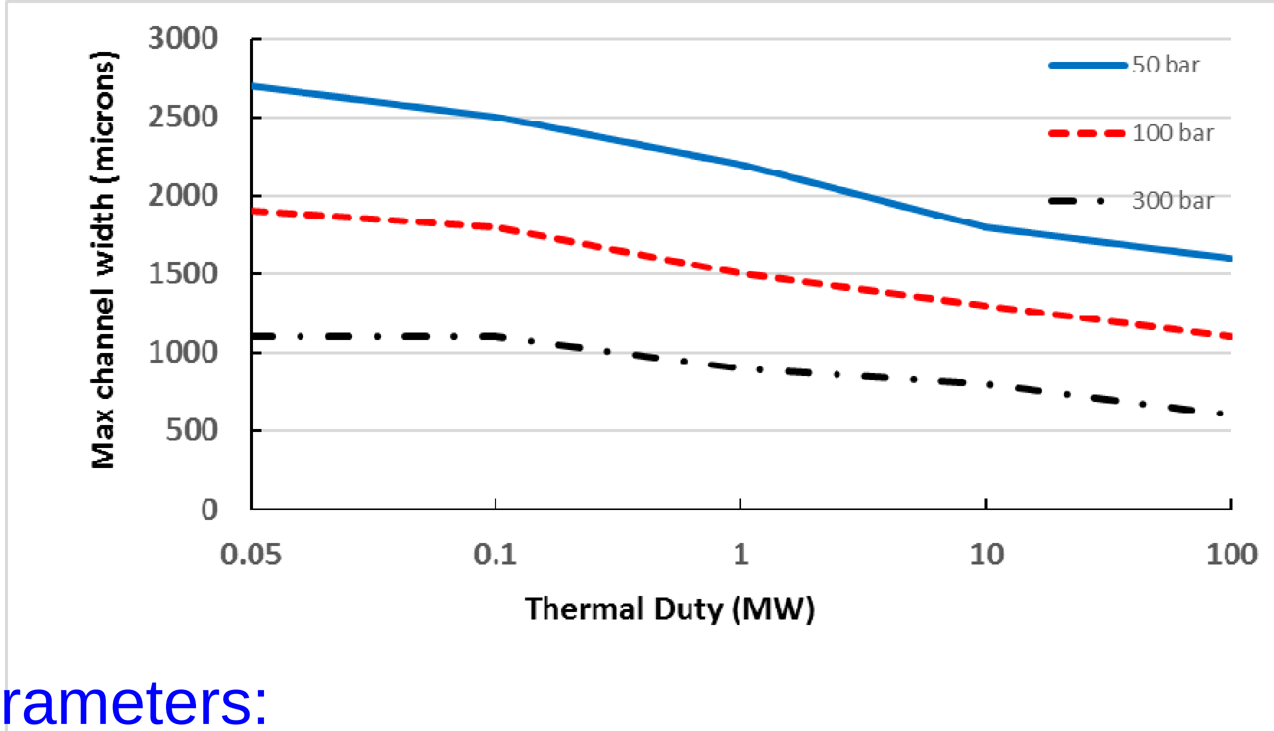
Microchannel Modeling - Effectiveness



- Design parameters:
- Re = 600
- channel height = 0.8 mm

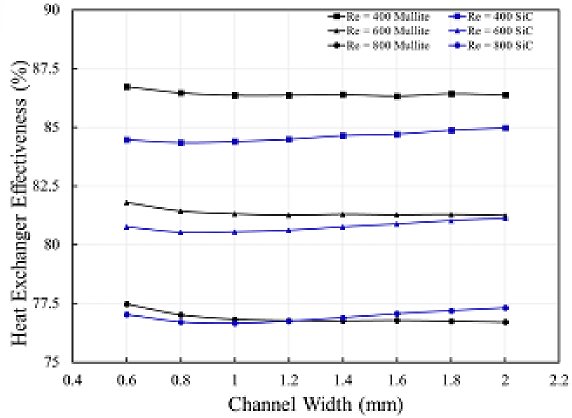
Microchannel Modeling - Reliability



Design parameters:

- System level failure probability = 1 x 10^{-6}
- SiC characteristic strength = 587 MPa, Weibull modulus = 6.4
- Heat transfer layer thickness = 1.2 mm (0.048")

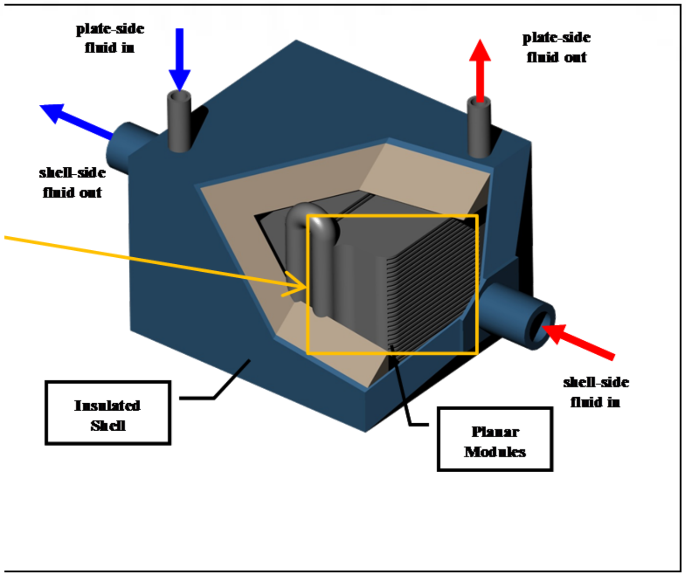
Microchannel Modeling – Material Selection



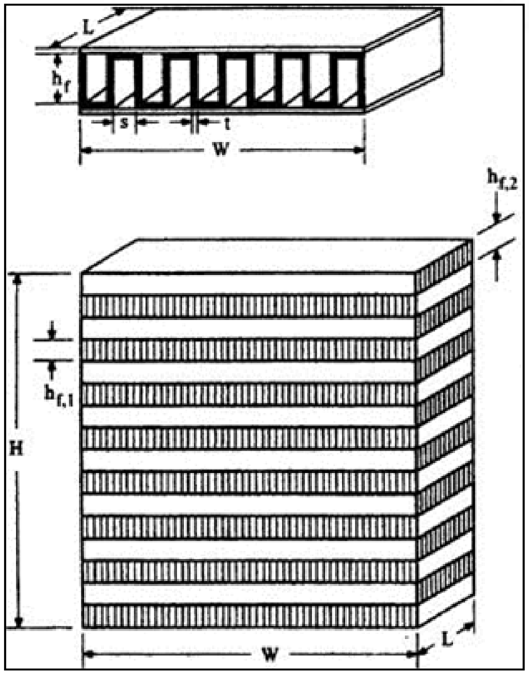
- Silicon carbide and mullite offer similar thermal performance.
- Silicon carbide has higher strength, higher thermal conductivity, and creep resistance.
- Silicon carbide is approx. 2-4x more expensive.
- Mullite is more oxidation resistant than silicon carbide.
- Silicon carbide has been selected for initial applications.

Design Options

Plate-Shell Design



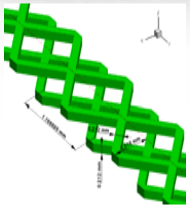
Block Design



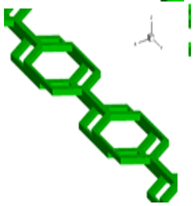
PCHE, FPHE, etc.

- Design options:
  - Plate-shell: microchannel plate/macrochannel shell
  - Block design

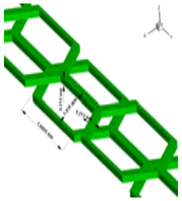
Compact Heat Exchanger Benefits



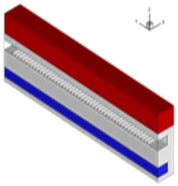
[Diamond Channels]
- 50% Overlap



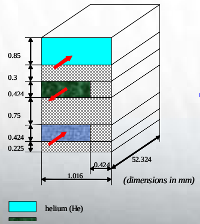
[Hexagonal Channels]
- 50% Overlap



[Hexagonal Channels]
- 100% Overlap



[Channels w/ Riblets]
- 0.1 mm
- 0.2 mm



[Straight Channels]

Higher surface/volume ratio and small transport distances provide higher effectiveness than conventional designs.

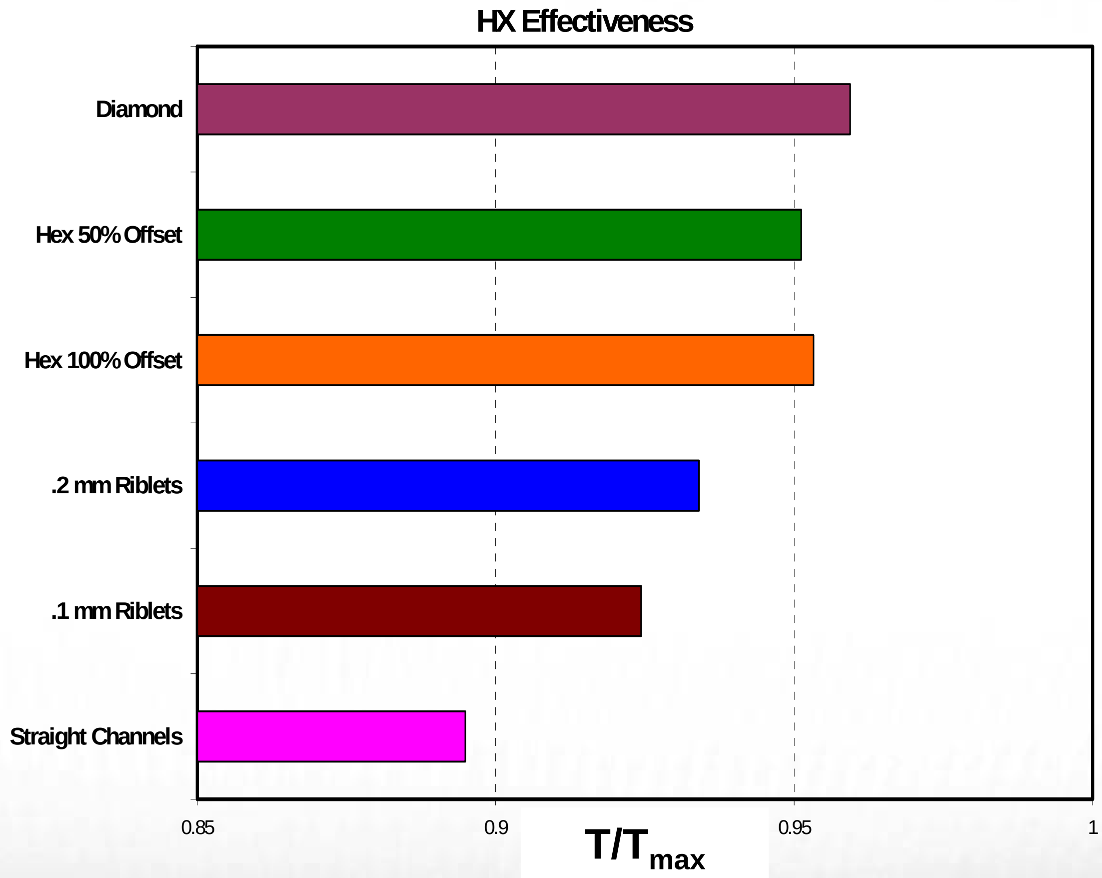
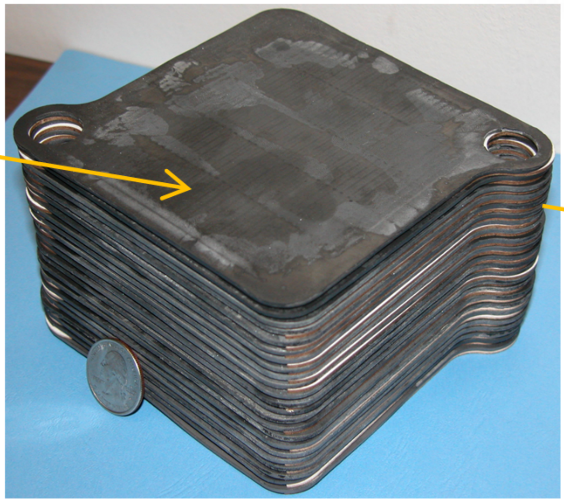
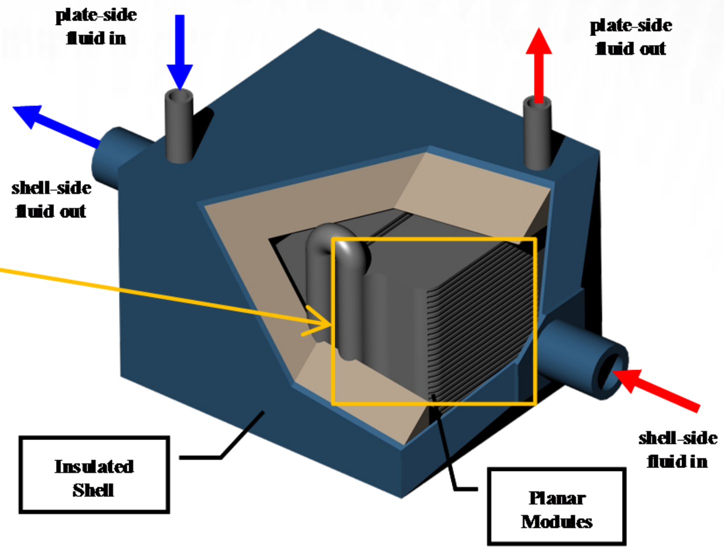


Illustration courtesy M. Wilson

Ceramatec Approach

Plate-Shell Design





- Individual plates as repeat units in modular stacks reduce net cost:
  - Downstream yield of full component
  - Simpler layup
  - Simpler binder removal
  - Simpler manifolds

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Laminated Object Manufacturing

1 **Powder processing**

2 **Slip preparation**

3 **Tape fabrication**

1 - Control surface area for slip properties and sintering.

2 - Disperse materials for uniform tape properties (featuring and lamination), defect elimination and controlled sintering shrinkage.

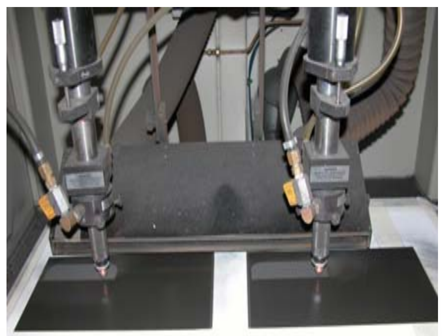
3 - Dry tape uniformly for uniform thickness, minimal drying stress, without defects.

Laminated Object Manufacturing

4 **Tape featuring**

5 **Tape lamination**






4 – Optimise power and speed to minimise heat affected zone, maximize throughput, and obtain accurate channel dimensions.

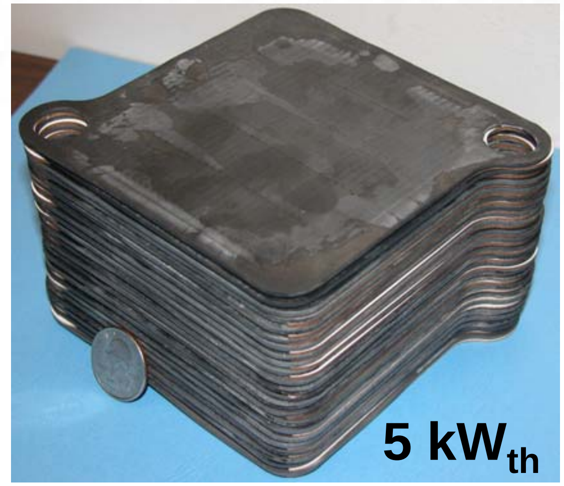
4 – Laser cut or punch depending on layer thickness and channel dimensions.

5 – Complete lamination for structural integrity without deforming internal features.

Laminated Object Manufacturing

6 **Sintering**

7 **Stack Assembly**



6 – Controlled thermal cycle/environment for binder burnout and densification to make leak tight components while maintaining flatness without creating defects.
6 – Complex designs require co-sintering dissimilar materials and porous and dense layers in the same component.
7 – Requires robust ceramic-ceramic joining.

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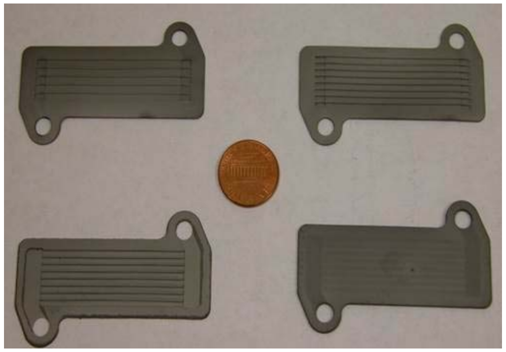
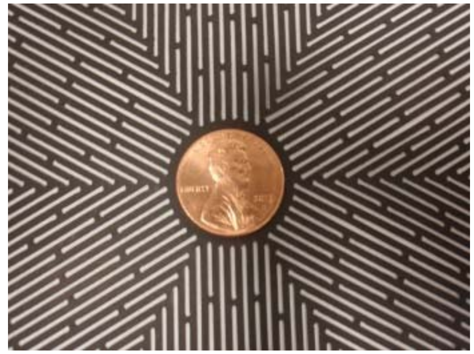
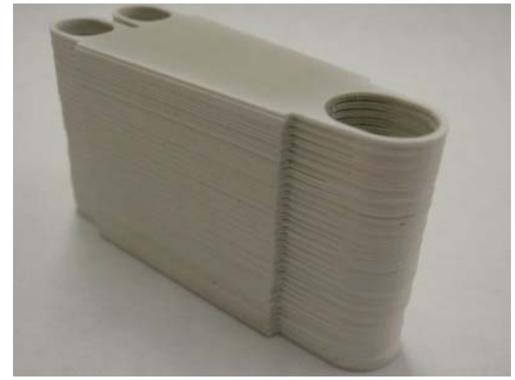
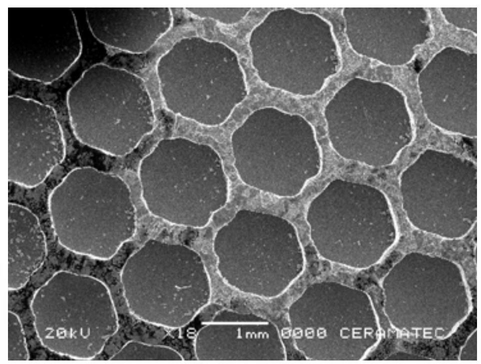
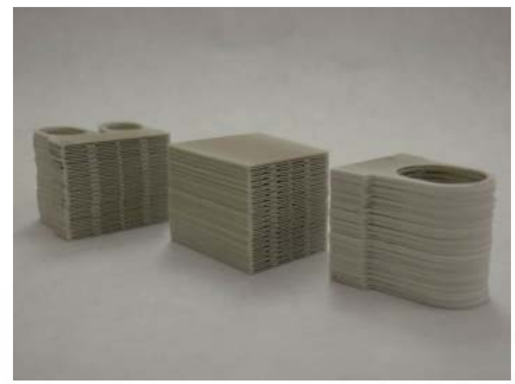
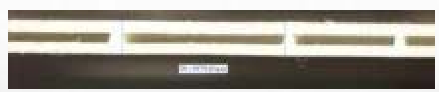
Microchannel Heat Exchanger
Design Flexibility



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Microchannel Heat Exchangers Performance Metrics

Performance Metric	Value
Thermal Duty	1 MW (heat)
Hydraulic Diameter - Feed	636μ
Hydraulic Diameter - Exhaust	1684μ
Temperature Span (Inlet to Inlet)	450C to 950C
Volume	1.0 m^3
Log Mean Delta Temperature	25C
Overall Heat Transfer Coefficient	145 W/m^2C
Area Density (modular stack)	310 m^2/m^3

Calculated values

- Scaleable from kW to MW
- Estimated ceramic heat exchanger cost: \$100-200 kW_{th}
- Reference case: gas separation modules: 100 \$/kW (independently verified by 3rd party for DOE).

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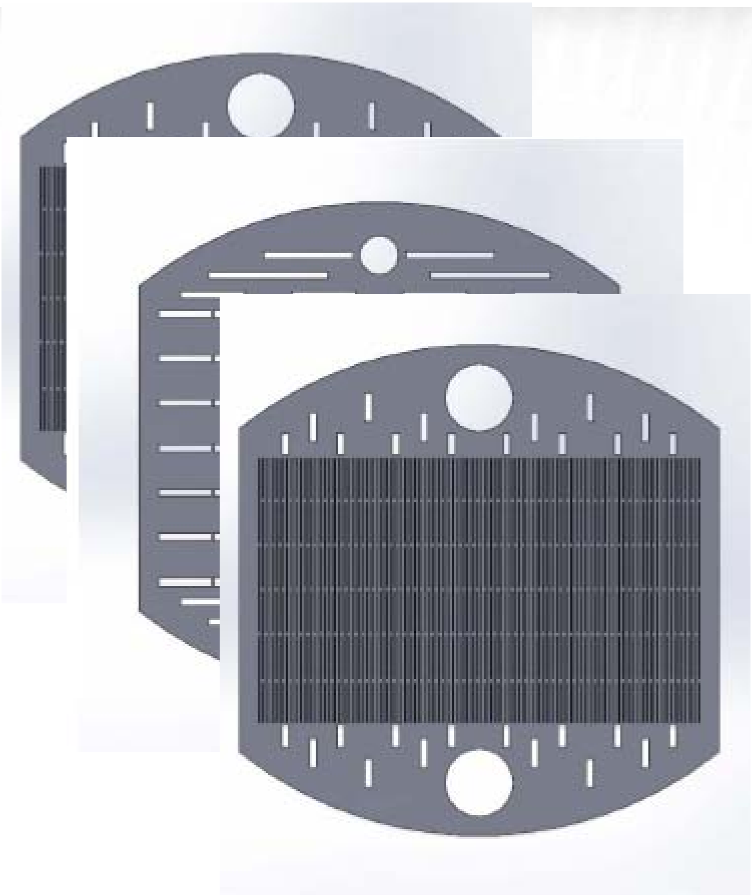
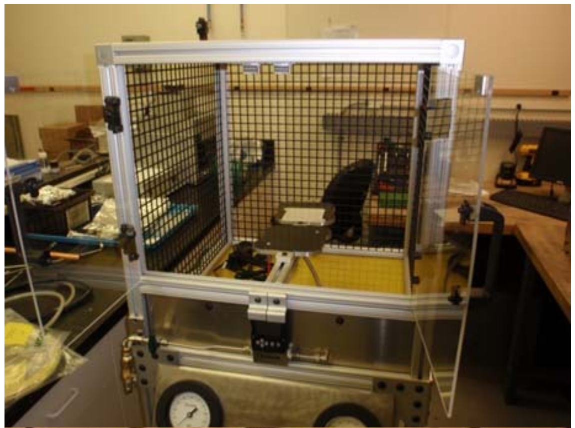
Plate Design

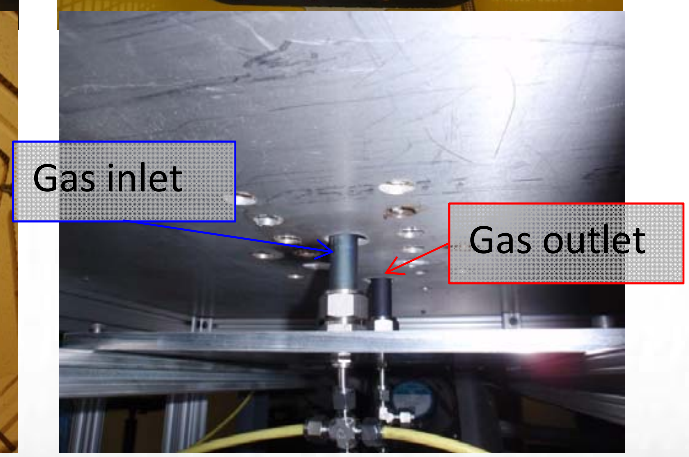


- Plate Shell design
- Flow distribution to channels
- Flow distribution across plates

Plate Fabrication and Testing

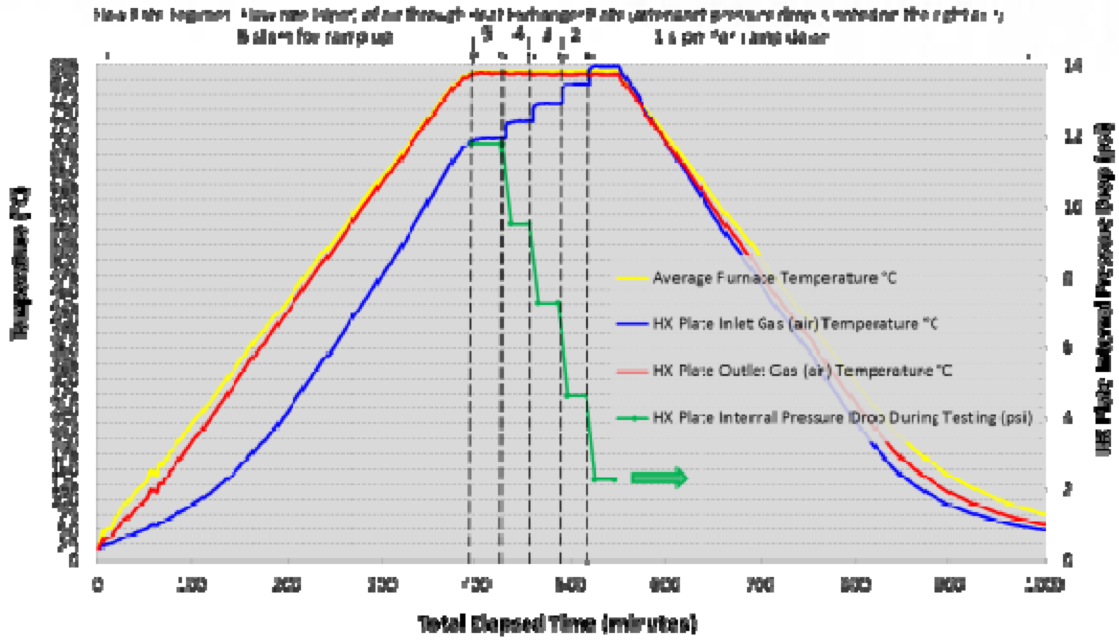
Individual Plates





Test Results

Individual Plates



Initial results:

- Plates and manifold pipes leak tight
- Moderate pressure drop
- Approach temperature > 100C for >5 slpm

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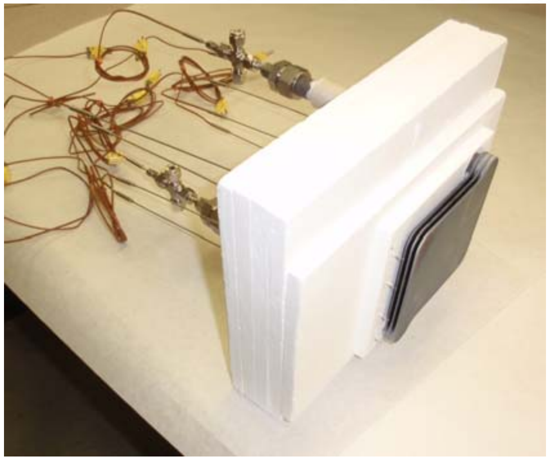
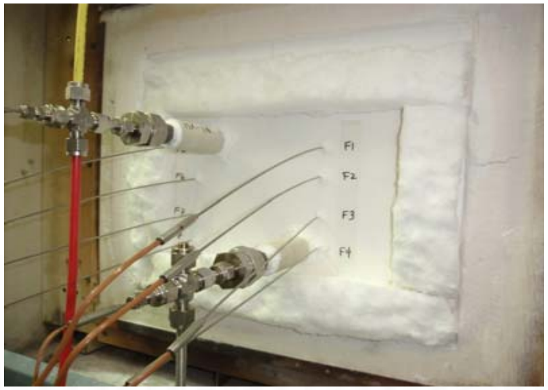
Test Apparatus

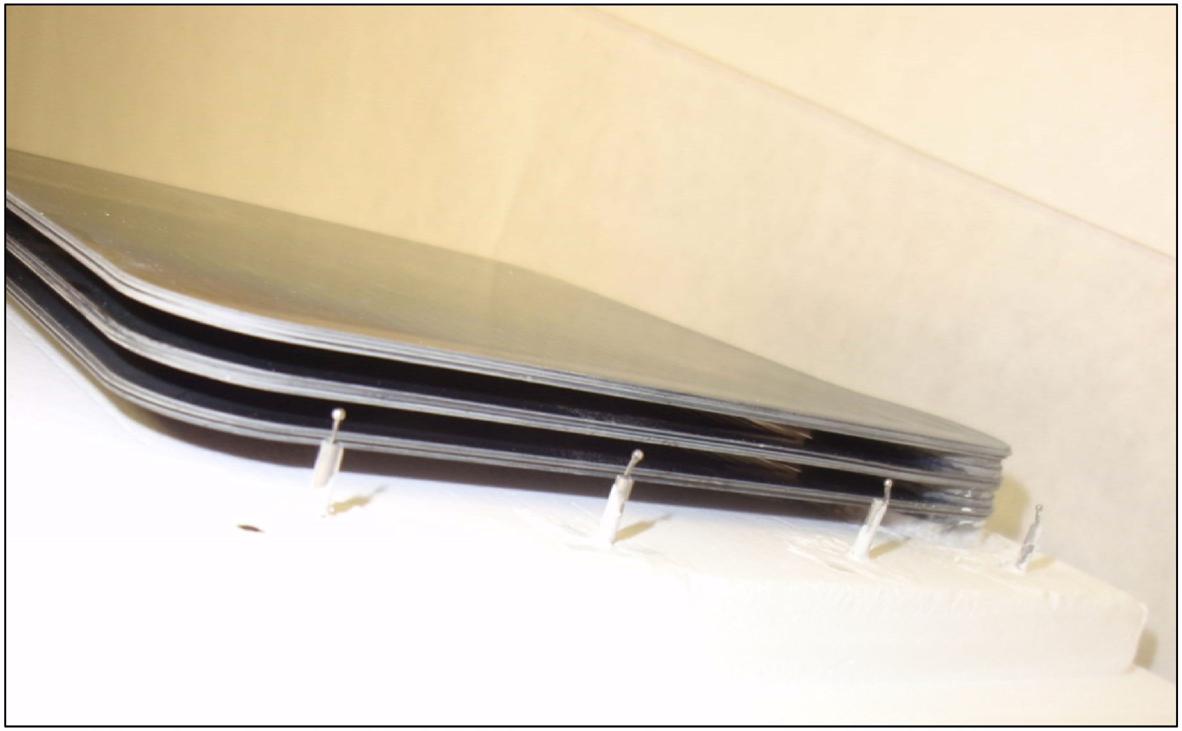
3-10 plate stacks





Test Apparatus

3-10 plate stacks

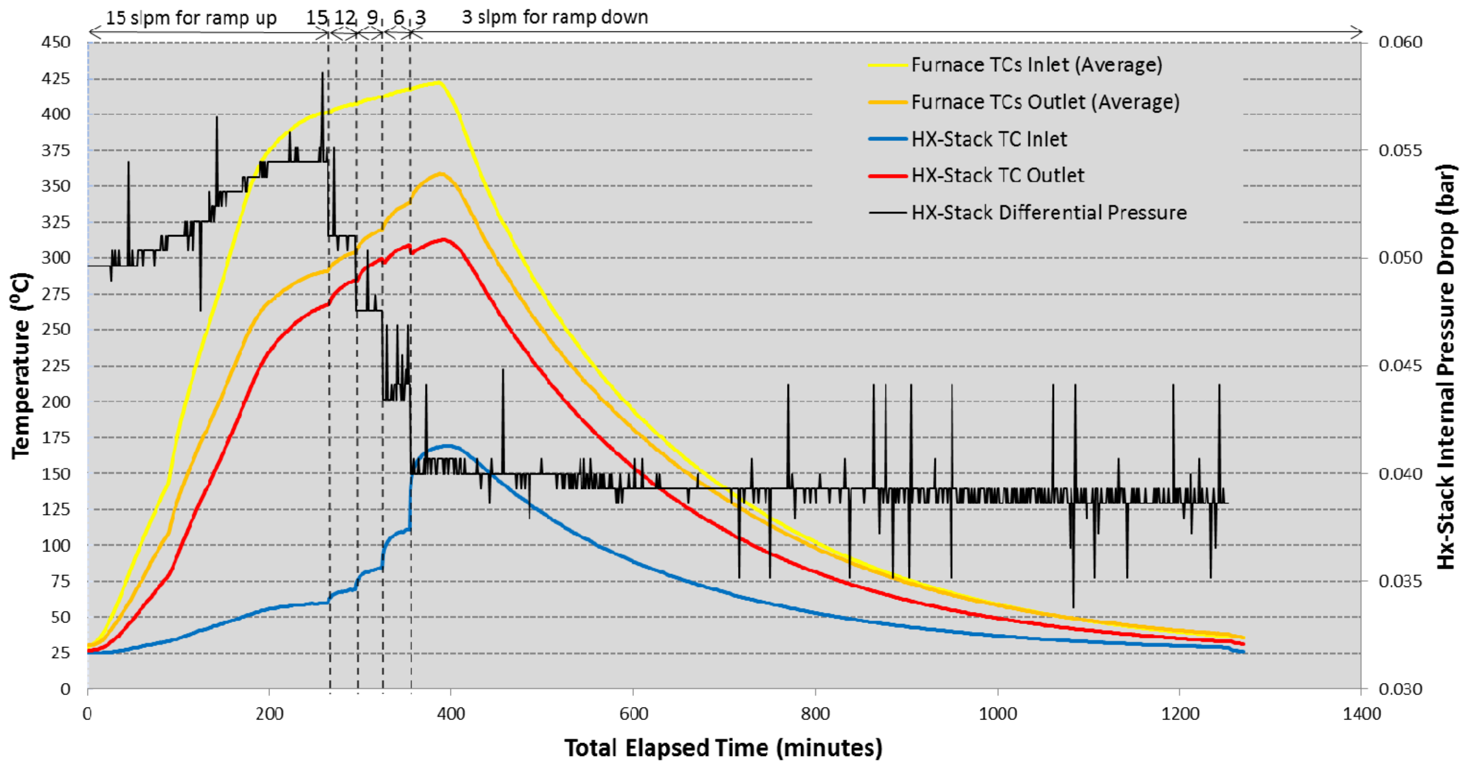


Measurements

Plate Temp in
Plate Temp Out
Channel Temp in
Channel Temp Out
Channel Pressure In
Channel Pressure Out

Test Results

3 plate stack



Preliminary results indicate good performance:
Good pressure drop – 4-5 kPa
Maximum effective heat transfer coefficient – 70 W/m-K
Maximum effectiveness – 65%

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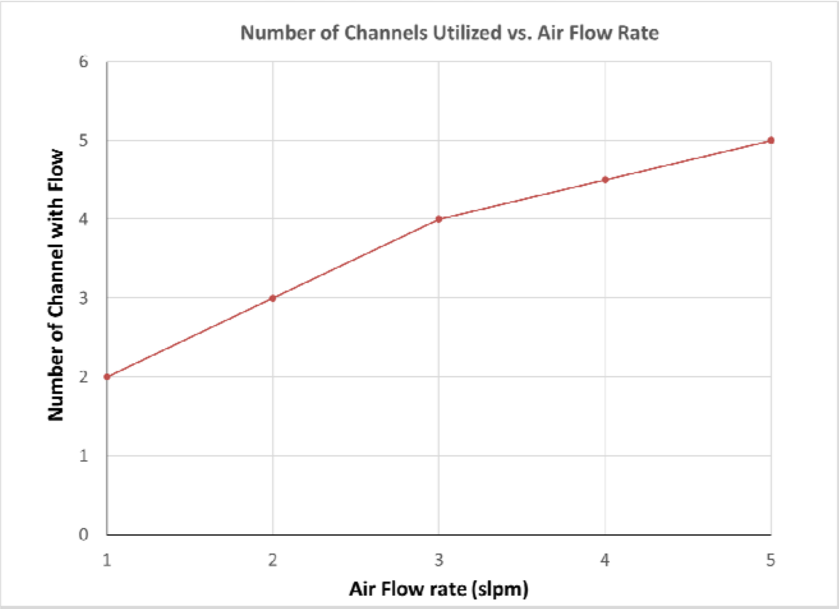
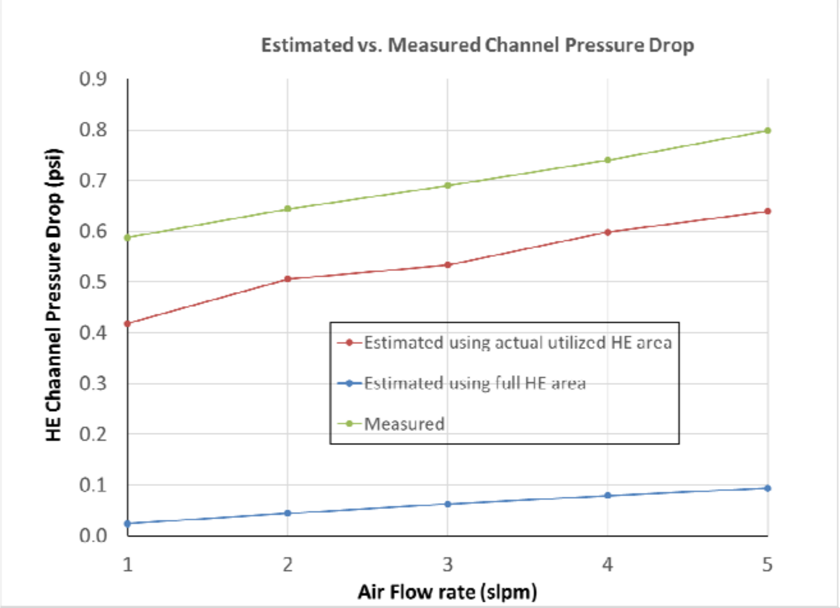
Test Results

3 plate stack

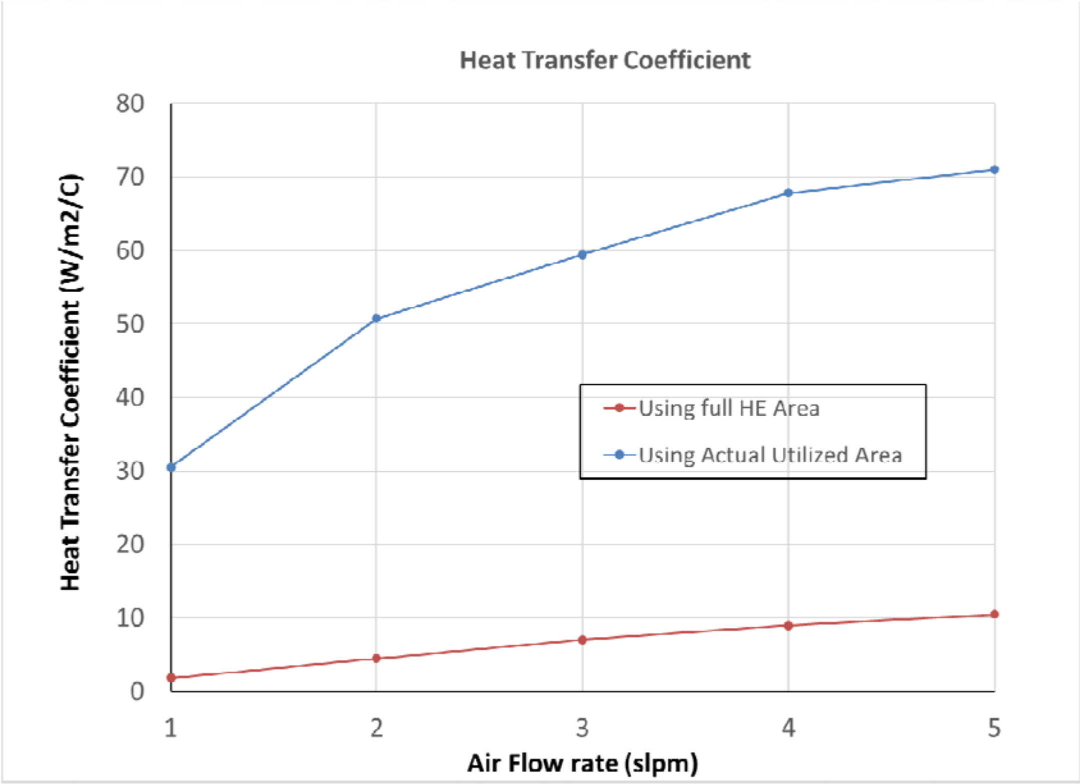




Test flow rates << design rates
Low flow leads to poor flow distribution and low utilization of HX plate area
Data agrees well with CFD models, assuming poor flow distribution

Test Results

3 plate stack



Assuming poor flow distribution, effectiveness demonstrates benefits of compact heat exchanger design are obtained.

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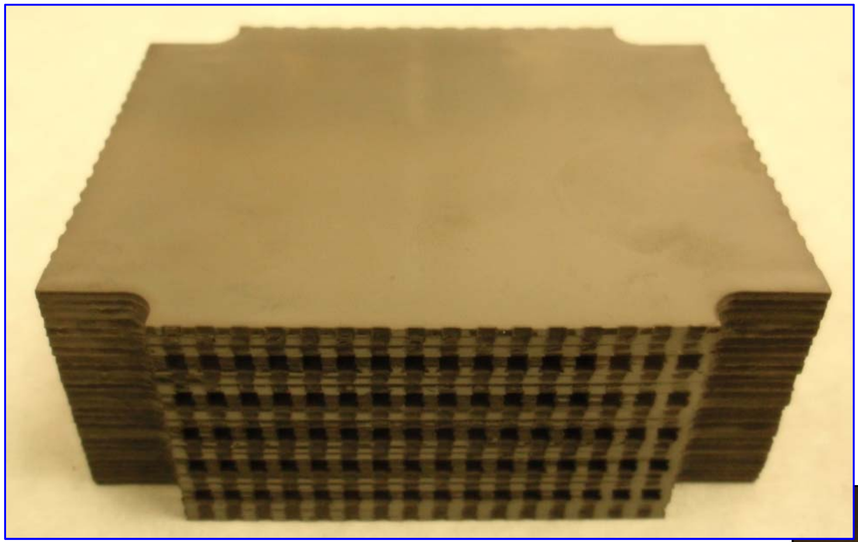
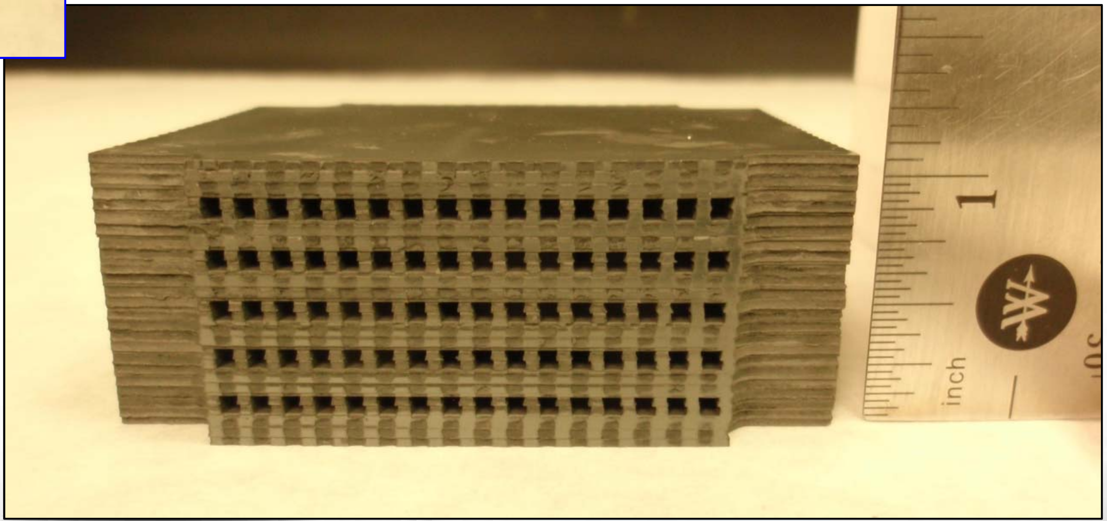
Demonstration: PCHE cross flow



Block Design

20-30 individual tape layers.
Featured, laminated, and sintered as one unit.
Successfully fabricated on second attempt.
R&D cost.



Further Risk Mitigation

Support mitigation of key technical risks, especially lifetime:

- Continue study and validation of design tradeoffs between design for manufacturing and performance.
- Materials testing: oxidation.
- Assembly of 5-10 kW stacks and n * 1000 h testing.
- Verify reliability of integration with balance of plant, especially hot gas manifolds.
- Verification of viable manufacturing costs for robust and scalable processes.

Summary

- Design parameters, materials, and commercially viable fabrication processes demonstrated for high effectiveness, low pressure drop, mechanically reliable ceramic, compact heat exchangers.
- Project is on track to demonstrate 5-10 kW heat exchange.
- A plan to mitigate risks for commercialization has been developed.

Acknowledgements

- US DOE NETL Crosscutting Technologies Award DE-FE0024077. Project Manager – Richard Dunst.

- Ceramatec: Angela Anderson, Kiley Adams.

- CoorsTek: SiC powder

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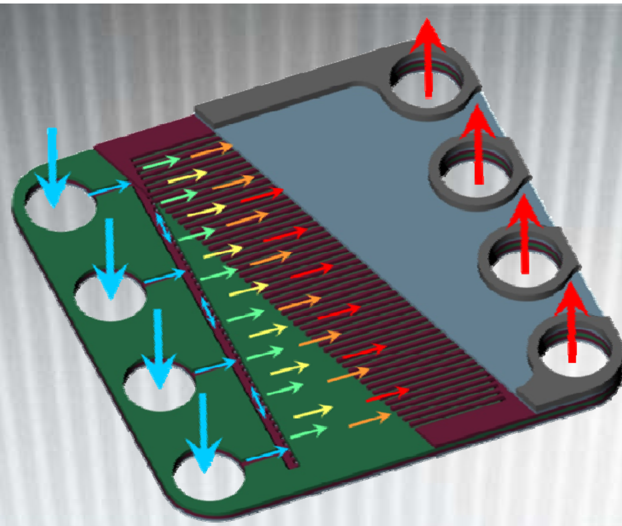

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Thank you. Questions?

Acknowledgement: DOE Office of Fossil Energy, Office of Crosscutting Technology, DE-FE-0024077.

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